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16. Abstract  The entire TAC study is briefly summarized for background information. The most important research items for the areas of noise, congestion, and emissions are identified. Other key research areas are also discussed. The 50 recommended research items are categorized by flight phase, technology, and compatibility benefits. The relationship of the TAC recommendations to the previous ATT recommendations is discussed. The bulk of the document contains the 50 recommended research items. For each item, the potential payoff, state of readiness, recommended action, and estimated cost and schedule are given.					
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# **ADVANCED SUBSONIC LONG-HAUL TRANSPORT**

## **TERMINAL AREA COMPATIBILITY STUDY**

### **Volume II--Research and Technology Recommendations**

**By Preliminary Design Department**

## **1.0 INTRODUCTION**

The emphasis of the Terminal-Area Compatibility (TAC) Study was airplane technology applicable to improved terminal-area operations for advanced, long-range aircraft. This study followed the previous NASA Advanced Transport Technology (ATT) Program (ref. 1). That program emphasized assessment of various advanced airplane features, including use of supercritical airfoil technology, to increase airplane cruise speed. One limitation of that study was that the advantages of increased cruise speed might, in fact, not be realized on future aircraft because of current bottlenecks and problems in the airport terminal area. This observation led to the current study, with emphasis on the congestion, noise, and emission problems of aircraft in and around principal airports. This emphasis represented a somewhat different orientation toward airplane design than in the past, when airplane efficiency was usually the principal concern. Therefore, it was desired that a primary output of this study be an identification of the research and technology required to support development of such a terminal-area-compatible airplane. While the major emphasis of the study and this report are R&T items associated directly with airplane technology, closely related areas, appropriate to agencies other than NASA, are also discussed.

The results of the study are reported in two volumes; this volume, which covers the research and technology recommendations, and volume I, which summarizes the entire study.

### **1.1 RESEARCH AND TECHNOLOGY DOCUMENT SUMMARY**

This study showed clearly that an aggressive research and technology program is essential to the future air transportation system of the United States. In the congestion area, the alternatives to technology improvements are the construction of many new airports (economically, sociologically, and politically difficult) or capacity falling far short of demand. The key research items (fig. 1) affecting congestion are (1) theoretical and practical studies of wingtip vortices and their control, and (2) the airborne hardware, ground equipment, and man/machine interface advances required for landing aircraft safely with the combination of close spacing, steep descent, rapid deceleration and turnoff, and poor visibility.

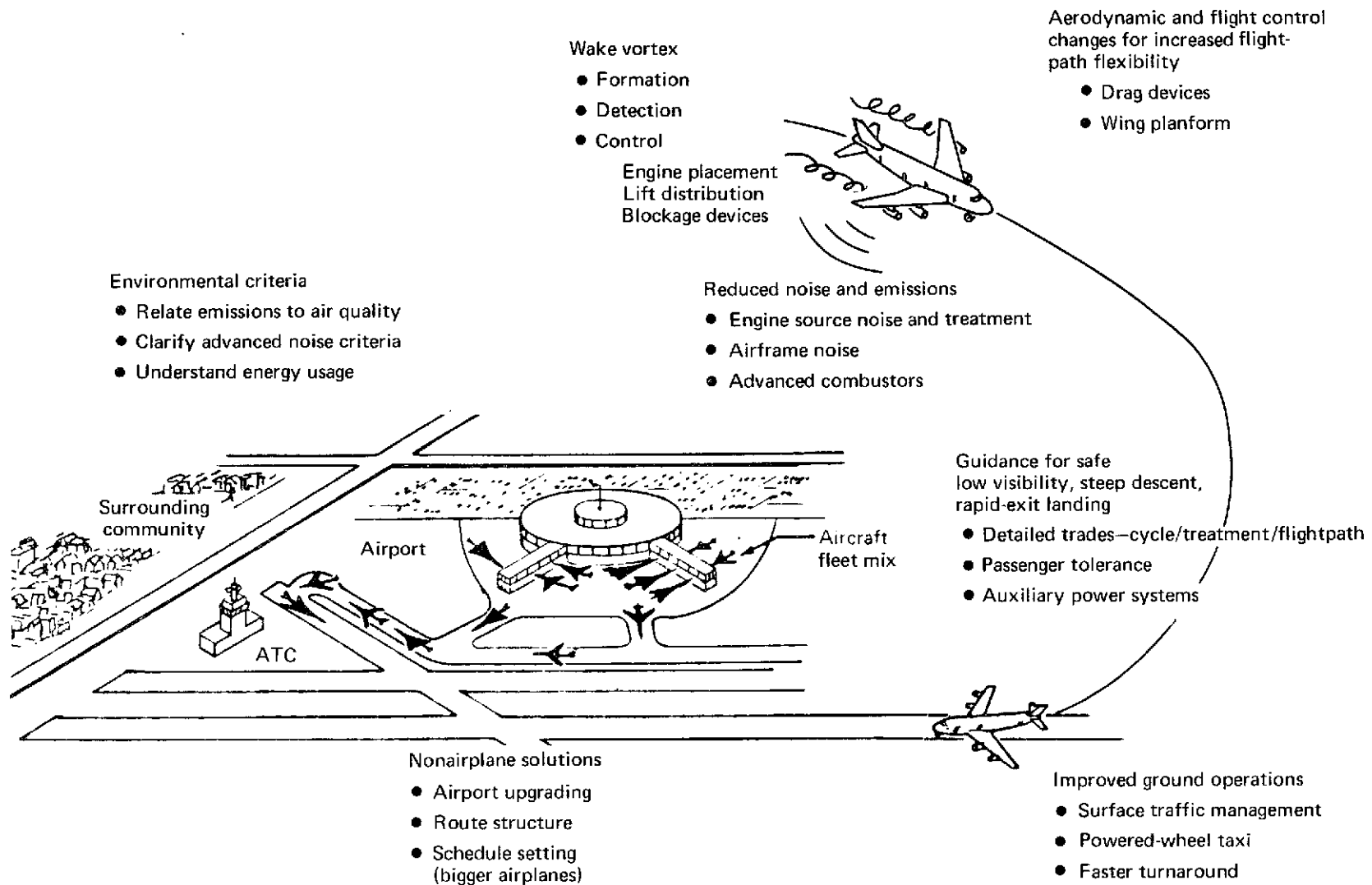


FIGURE 1.—TERMINAL COMPATIBILITY SOLUTIONS AND KEY RESEARCH

In the noise area, research is necessary in the areas of low-noise engines, airframe noise, noise treatment/abatement trades, drag devices, and noise criteria that better relate the parameters of airplane design to community acceptability. In the absence of these data, designs that are nonoptimum in terms of economics and fuel use will result from arbitrary noise requirements.

Similarly, in the congestion areas, key research items include the means and cost of engine emission control and much improved terminal-area air pollution models, so that knowledgeable trades between operating economics, fuel consumption, and the true effect of airplanes on air quality can be made.

In addition, the increasing complexity and sophistication of airplane systems required to improve the airplane in the above three areas requires research in the area of maintenance to retain good airplane economics. Items include improved reliability, improved maintainability, and more extensive maintenance monitor systems.

Although the study was primarily aimed at airplane technology, some other areas of needed research were identified. Key items are those related to airport capacity, including surface traffic control systems, and the whole airplane/ground system interface.

The TAC study was based on the assumption that the research recommendations of the ATT study would have been carried out successfully. A review of the ATT recommendations indicated that they and the TAC recommendations do indeed complement each other and that both are essential.

The time scale of the approaching terminal-area compatibility problems and the duration of some of the key research packages are such that immediate initiation of ATT and TAC research is vital. In addition, the logical planning of some of the research packages in a series of sequential phases will lead to near-term application of intermediate research outputs.

Section 2.0 of this document presents sufficient background data to help understand each of the recommended research programs described subsequently. A brief description of the airplane design changes made to improve terminal-area compatibility is provided first. The various proposed research activities are then described in terms of functional, technological, and airplane component design categories. The relationship of this proposed work to earlier technology efforts proposed under the ATT program is described. Finally, a brief assessment of the R&T costs in relation to the potential dollar value of realizing the research goals is discussed.



Section 4.0 contains individual research work statements divided according to applicability to airplane approach, ground, takeoff, and cruise operations. In some cases, the assignment of a research item to one of these categories is arbitrary, since many developments will affect more than one phase of flight. Each work package identifies, qualitatively, the potential payoff, current status, principal tasks, and approximate cost and schedule required to advance the state of the art. It should be emphasized that the projected costs and schedules are best-judgement estimates.

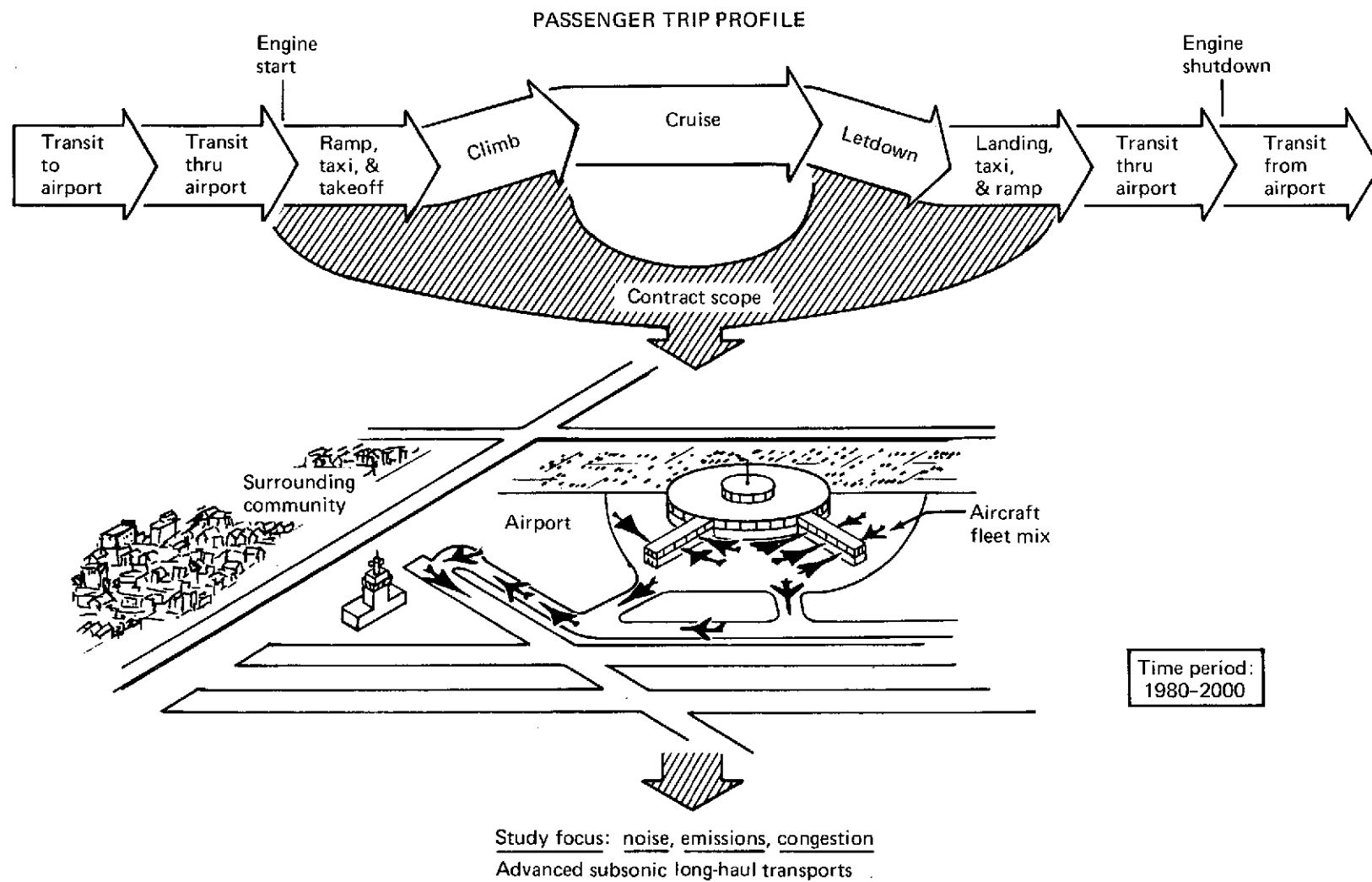
Many of the research packages in this volume could be carried out using the Research Support Flight System (RSFS—NASA 515, a 737 airplane and its installed avionics system) and are similar to experiments planned for that program. This includes evaluation of advanced avionics equipment and its integration with the airplane and the ground system, as well as programs requiring extensive airborne data gathering, such as VLF navigation and wind model development. Other research packages could be carried out on the RSFS with suitable modification, if layup time for such modification could be integrated into the schedule later in the Terminal-Configured Vehicle (TCV) program. No attempt was made in the TAC study to coordinate the scheduling of the research packages recommended here with the TCV program or with other NASA or DOT research programs.

## **1.2 STUDY SUMMARY**

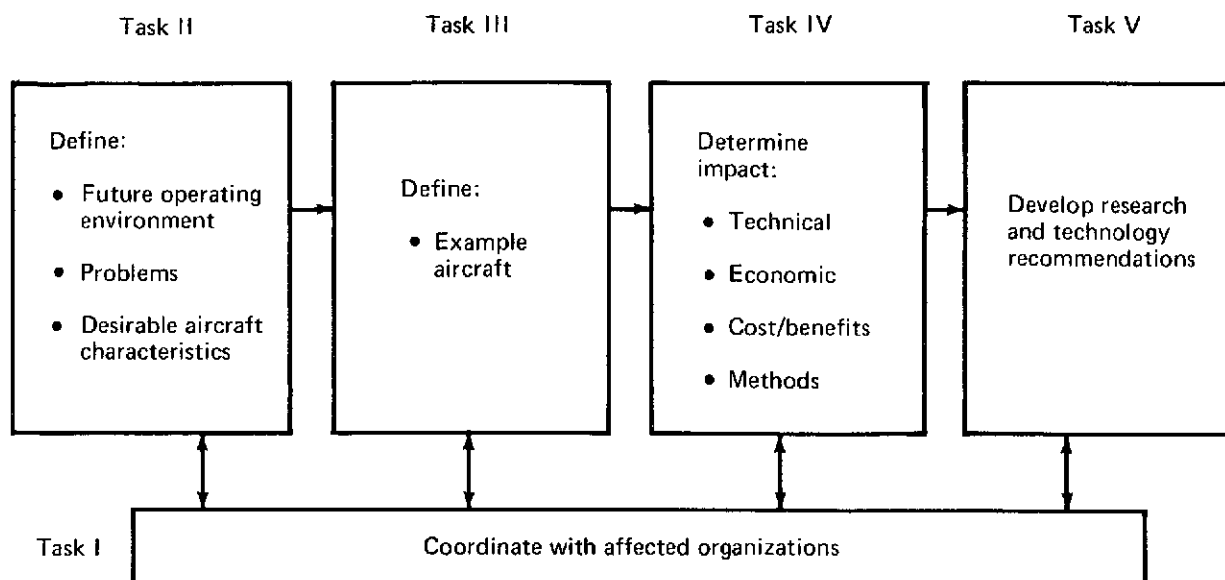
This study identified airplane research and technology necessary to ensure that future airplanes have the capability to meet forecast traffic demand without adverse effects on airport communities. The potential costs and benefits of this research were estimated.

The scope of the study can be illustrated by considering the functions involved when a passenger embarks on a typical airplane trip (fig. 2). The study was an 11-month effort that encompassed five specific tasks, with emphasis directed to the functions involving the airplane from engine startup to shutdown. The relationships of these five tasks are illustrated in figure 3 and described briefly in the following paragraphs.

Task I involved coordination of the study results with interested groups comprising various elements of the air transportation system to ensure that the assumptions and recommendations of the study were consistent with their experience and plans. These groups included airlines, various airport authorities, and FAA personnel both in regional offices and at the FAA headquarters in Washington, D.C. In addition, discussions were held with other technology-oriented groups, such as NASA, and other elements of the aviation industry, such as the engine manufacturers.



**FIGURE 2.—PROGRAM SCOPE**



*FIGURE 3.—STUDY TASK DEFINITIONS*

The bulk of the technical effort expended in the study was contained in tasks II, III, and IV. Task II, Compatibility Definition, sought to project the impact of future aircraft operations on typical large major urban airports, to evaluate characteristics desirable in an advanced aircraft, and to promote improved terminal compatibility. The method included: making traffic projections out to the year 2000; refining these projections for three specific airports, J. F. Kennedy, O'Hare, and Los Angeles International, as examples; projecting the future air traffic control technology and environment; and, finally, combining this information to estimate future congestion, noise, and emission situations for the airports of interest.

Studies were made of the impact on each of these characteristics of several sets of assumptions. A baseline assumption, included in all of the task II projections, was that nothing would be done to the operational characteristics of the advanced aircraft beyond the capability provided by current airplanes. Under this assumption, and under the driving force of increased traffic projections, calculations were performed to study how current congestion, noise, and emission situations might change.

Beyond this, several different "futures" were projected. Each of these futures consisted of increasingly advanced technology assumptions concerning the pertinent capabilities of the airplane, the community, the airport, and the air traffic control system. These advanced-technology futures were then evaluated with respect to assumed goals of congestion, noise, and emissions. These data were compiled to show the potential improvement to airplane/airport compatibility.

From these studies, broad desirable characteristics were inferred to which the terminal-area-compatible airplane might be designed. Identification of these characteristics was the final output of task II.

In task III, Compatible Airplane Definition, the feasibility of achieving these desirable capabilities at nonprohibitive cost was examined by designing airplanes with configuration concepts and innovative devices that would give the needed capability. To accomplish this, a Mach 0.9, 200-passenger, 5556-km (3000-mile) range airplane, previously developed under the ATT contract, served as a baseline configuration. Then, based on the desirable characteristics identified in task II, design modifications were made to the baseline airplane. Since it was not within the study scope to

develop detailed design trades, the modifications were based on brief studies into each of the technology areas of interest. In many cases, design decisions were made on the basis of experience and sound engineering practice. The final output of task III consisted of definition of the TAC airplane.

The study included an assessment of the TAC airplane under a further restriction that the airplane be capable of using runway lengths on the order of 1524 m (5000 ft). Thus, a second airplane, designated TAC-RTOL (a reduced takeoff and landing version of the TAC airplane) was also configured. In addition, a third reference airplane was designed which used current technology and operational procedures. This airplane was based on current widebody transport design. Configuration of these airplanes concluded task III.

Task IV, Impact Assessment, evaluated the technical and economic impact of the design modifications introduced to the baseline airplane to provide terminal-area compatibility and to provide the RTOL capability. An assessment of the impact was made by comparing the baseline and the TAC airplanes in terms of airplane takeoff gross weight. Beyond that, however, an economic assessment in terms of airplane direct operating costs (DOC) and net present value (NPV) were also made.

Task V involved distilling the results of the complete study into a series of recommendations identifying research and technology that (1) showed cost-effective potential and (2) was found necessary to support the concept of terminal-area-compatible aircraft. As noted earlier, these recommendations constitute the principal output of the study and, accordingly, have been documented separately in this volume.


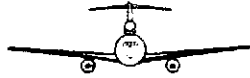
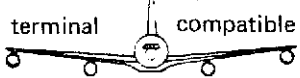
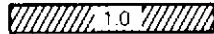
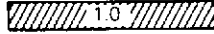
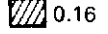


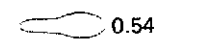
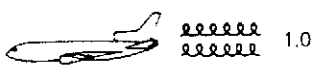





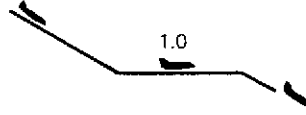
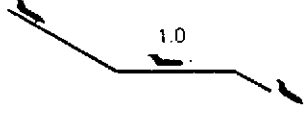
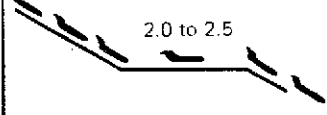
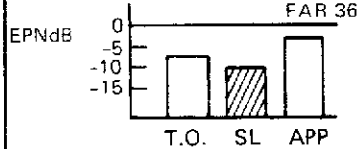
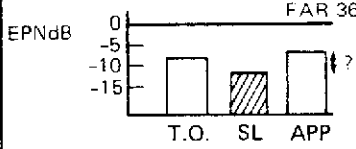
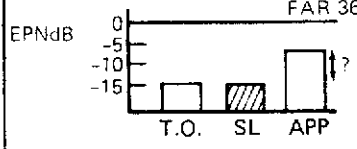
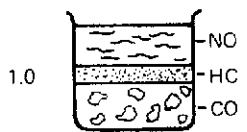
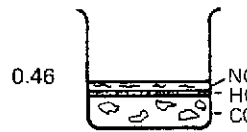
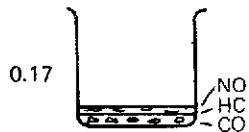



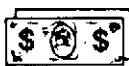
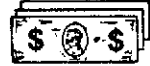
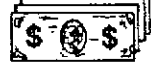
Item	Present technology  CWB	Advanced technology  ATT	Advanced technology terminal compatible  TAC
Projected airport impact			
Congestion Relative peak hour delay—typical airport	 1.0	 1.0	 0.16
Noise Relative 90 EPNdB noise-affected area	 1.0	 0.68	 0.54
Emissions Total pollutant tonnage	 1.0	 0.5	 0.2
Relative airplane characteristics			
Gross weight Takeoff weight	 1.0	 0.89	 0.93
Runway operations Runway efficiency—arrivals/unit time	 1.0	 1.0	 2.0 to 2.5
Noise Relative to FAR 36 station noise	 1.0	 0.89	 0.93
Emissions Kilograms per landing/takeoff operation	 1.0	 0.46	 0.17
Airplane economics			
Operating costs Relative DOC	 1.0	 0.95	 0.90
Net present value Relative dollars	 1.0	 1.45	 2.20

FIGURE 4.—SUMMARY COMPATIBILITY ASPECTS

Results of the principal calculations made in this study are given in figure 4. Key points include:

- a) Congestion at major airports results in considerable inefficiency today and will become worse in the future. Airplane modifications cannot alone solve the problem; however, if sufficient R&T emphasis is applied, one approach to congestion reduction can reduce delay times by 84%. This approach is contingent on an as-yet-undemonstrated solution to aircraft wake turbulence.
- b) Noise restrictions exist today at some major airports. This further compounds the congestion problem. Future noise problems show signs of improvement as newer, noise-designed aircraft replace earlier, less quiet aircraft. Further gains in noise improvement appear possible if vigorous R&T efforts enable projections to be realized at acceptable cost. The use of improved airplane takeoff and approach paths may offer an attractive alternative to extensive engine treatment, particularly when fuel use is considered.
- c) Aircraft emissions may not be a problem. However, the extent to which such emissions must be considered could not be determined since airport pollution tonnages are difficult to interpret in terms of air quality impact. Today's airport tonnage levels are about evenly divided between automobiles and aircraft; future trends show greater relative aircraft contributions. Oxides of nitrogen, as a proportion of total tonnage, will increase relative to carbon monoxide and hydrocarbon pollutants, reflecting the scarcity of satisfactory control techniques. Research and technology efforts can improve the situation. A terminal-compatible airplane using advanced combustors and a "powered" wheel, and operating in ground-delay-free airports, will be 83% cleaner than today's widebody aircraft.
- d) A fleet of terminal-compatible airplanes could potentially realize sufficient cost savings, due to delay reduction, to more than offset the costs due to incorporation of congestion-reducing design modifications. In fact, the delay savings would offset the costs of the noise and emission modifications as well.
- e) In the absence of vigorous research and technology efforts, the above improvements will not take place, and existing problems will be compounded.

Some additional pertinent study results are summarized below.

With respect to congestion, today's traffic demand was found to already exceed the capacity of some major airports at peak hours, and this demand will increase severalfold by the year 2000. Meeting this demand by airplane changes alone, without additional airports or artificial demand constraints, was shown to be infeasible; a coordinated air transportation system capacity expansion program is required as well as airplane improvements. The major bottleneck in the flow of traffic was shown to be the safe interval between airplanes using a runway. This is currently determined by safety considerations related to wing trailing vortex (wake turbulence) characteristics of large aircraft.

Expected advances in ATC, airplane, and airport characteristics will leave wake-turbulence effects and the time an airplane must spend on the runway as the limiting factors in the future. The latter factor can be reduced severalfold by improved automatic braking and steering systems, with passenger comfort and pilot workload setting the limits. The wake-turbulence problem is poorly understood today; one proposed solution was assumed and studied to assess the magnitude of penalty incurred. A 2% takeoff gross weight increase was calculated for all of the congestion-reduction modifications. Extensive research activity to understand the basic physics of vortex formation, strength, stability, and means of control is urgently needed.

The present study showed that eventual replacement of current aircraft with a fleet complying with FAR Part 36 (noise levels at specified ground points) will effect a 20% reduction in ground area affected by airplane noise by the year 2000. However, within the study requirement that the noise impact on the community be reduced to an acceptable level solely by changes to the airplane, rather than in combination with improved airport area land use, further reduction of airplane noise was studied. Under such conditions, noise reductions could be achieved only with adequate R&T funding (and then only at increased operating cost) by increasing engine and nacelle treatment. With such treatment, and if improvements are also assumed for derivatives of current aircraft, it was determined that ground areas heavily impacted by noise could be approximately contained within the boundaries of typical large airports by the year 2000.

Additional airplane contributions to noise reduction by means of improved flightpaths were also studied. Assessed operational and design features included steep descents, shorter takeoff runs, and steeper climb gradients, all as means to keep the airplane farther from noise-sensitive areas. Such flightpath flexibility required shifting the basic airplane design more toward low-speed aerodynamic optimization, addition of controllable drag devices, and expanded guidance and display systems to maintain safety and accuracy. The results suggest that extensive treatment, together with flightpath improvements, may be redundant with respect to noise improvement on advanced transport aircraft. One current roadblock concerns the lower practical limit on source noise reduction due to the aerodynamic noise of the airplane interaction with the air. Research is needed to determine the level and means of controlling it.

The effect of airplanes on air quality cannot be accurately determined with current lack of knowledge of (1) the effects of individual pollutants on people and (2) the physics of pollutant motion through the atmosphere. With the characteristics of today's automobiles and factories, the airplane is not a major source of pollution. However, as automobile and industrial emissions are reduced, as the number and size of airplanes increase, and as our knowledge of emittent effects is improved, it will be necessary to review the relative pollutant contribution of the airplane.

This study has shown that engine manufacturer projections of future combustors will enable an appreciable reduction in the amount of emissions per unit of fuel burned. In addition, informal discussions with the manufacturers suggest that these gains for new, advanced engines may be achieved at minimal additional cost. Moreover, if airport congestion can be reduced or better coordinated control of aircraft movements on the ground effected, then significant improvement in carbon monoxide and unburnt hydrocarbon emissions will be achieved since these are primarily produced during ground operation.

Further reduction, if necessary, has been demonstrated by incorporation of internally driven wheels as an alternative to main-engine taxi propulsion. The "powered" wheel may help to achieve a successful low-pollutant combustor design that typically must confront conflicting requirements between carbon monoxide/hydrocarbon reduction and reduction of oxides of nitrogen by allowing a combustor design biased toward control of the nitrogen oxides. It may also provide ground movement flexibility in the terminal area with less ground equipment.

The airplane configuration task exposed a number of interacting design requirements imposed to handle the various congestion, noise, and emission modifications. Drag brakes, for example, were incorporated to enable steep descent to achieve approach-noise reduction. However, these brakes might in fact add to "airframe" (nonpropulsive) noise.

Generally, potential design resolution of conflicting requirements was able to be achieved. One exception to this concerned the study to provide RTOL (reduced takeoff and landing) capability to the terminal-compatible airplane. The intent was to provide greater flexibility for route structures to avoid the most congested airports. Use of an overwing propulsion installation on a four-engine configuration to achieve improved takeoff lift coefficients resulted in significant cruise penalties. This further conflicted directly with the wing vortex control technique of an extreme spanwise outboard engine location. This conflict was not resolved.



The airplane that was designed to meet the terminal-area goals weighs about 3% more than its counterpart, which is not terminally configured. However, economic savings associated with the reduction in delays due to its higher traffic flow capabilities more than offsets this factor, and the direct operating cost is calculated to be 6.0% lower than for a reference advanced-technology airplane designed primarily for the cruise condition. This is in addition to the less easily accountable benefits of the noise and emission reductions to the community at large.

While this study was primarily aimed at potential airplane improvement, various characteristics of the rest of the air transportation system and related areas that are necessary or desirable were recognized. Prominent among these are:

- a) Ability of the airport terminal to handle larger numbers of airplanes and people
- b) Continued development of an air traffic control system such as the tentatively planned advanced air traffic management system
- c) Coordinated development of secondary airports and appropriate airplanes and surface transportation links to supplement the primary airport/airplane network
- d) Development of technology and broad economic and social value models leading to rational, cost-effective noise and pollution limits for each source
- e) Initiation of studies leading to improved awareness of the relationship of energy use to aircraft design in general and terminal compatibility in particular.

The overall conclusion to be drawn from this study is that major problems associated with airplane terminal-area operations can be predicted, that a number of potential airplane improvements can help to solve these problems, and that extensive, timely research and development is necessary to make such improvements technically and economically feasible.

## 2.0 SUMMARY OF RESEARCH AND TECHNOLOGY RECOMMENDATIONS

### 2.1 IDENTIFICATION OF REQUIRED TECHNOLOGY

Some introductory comments are in order prior to detailed enumeration of the various proposed research efforts. Four airplanes were configured in the course of this study to help understand the role of design changes and technology advances. These are summarized in table I.

Relative to the baseline ATT airplane, several specific modifications were made to improve the terminal capability of the long-haul transport. Figure 5 gives an overview of these changes. A major change, obvious in comparing the TAC and ATT airplanes, was from a three-engine to a four-engine airplane. This was done to provide flexibility for positioning the outboard engines near the wingtip as a method of tip vortex control without undue tail size for engine-out control. Tip vortex control was also the motivation for the mechanical device shown at the trailing edge of the outboard wing position.

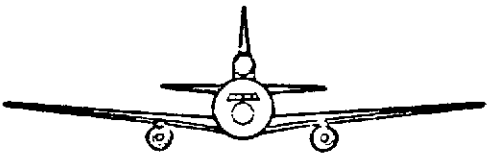
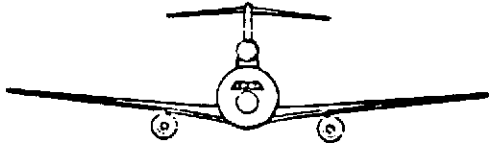
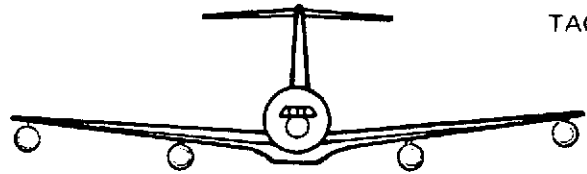
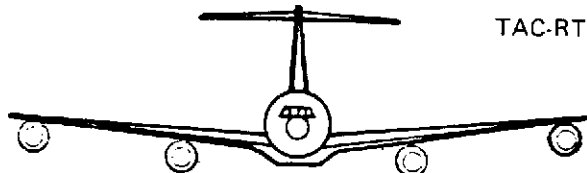
The reasons for these two design changes are discussed in more detail in volume I of this document. The second design change concerns an increased aspect ratio for the TAC wing. In addition, wing area was increased to improve low-speed aerodynamics and thereby reduce airplane noise impact on the community. A third design change is the aft end of the TAC airplane fuselage where large deployable drag brakes have been incorporated. This design change was motivated by the requirement for achieving steep, noise-abatement descents on approach.

Some changes were made to the engines, primarily through incorporation of an advanced combustor to decrease engine emissions. A smaller change involved a slight modification of the engine cycle toward reduced overall pressure ratio, again to reduce emissions.

Another modification included incorporation of a powered-wheel device for providing low-speed taxi without use of the main propulsion engines. Incorporation of the powered wheel required increasing the size (relative to the ATT airplane) of the auxiliary power unit to drive the wheels. At the same time, the APU was further oversized to provide an in-flight APU capability for driving all the auxiliary power systems for the TAC airplane. For reasons discussed in more detail in volume I, this design modification was made to effect additional noise reduction through the ability to realize lower throttle settings for the airplane on approach.

Further design changes made to the airplane included increasing the braking material in each of the landing gear wheels to provide the capability for high-speed deceleration without compromising

TABLE 1.—FOUR STUDY AIRPLANES

Configuration	Airplane acronym	Reason for configuration development
 CWB	CWB Current widebody	Serves as technology and economic baseline representative of today's widebody jet transports
 ATT	ATT Advanced transport technology	Serves as technology and economic baseline representative of projected 1985 technology with design based principally on efficient cruise capability
 TAC	TAC Terminal area compatible	Serves to identify and assess design changes desirable for improved airplane/airport compatibility
 TAC-RTOL	TAC-RTOL Terminal area compatible—reduced takeoff and landing	Serves to identify airplane impact for 1524 m (5000 ft) runway capability (TAC airplane configured for 2530 m (8300 ft))

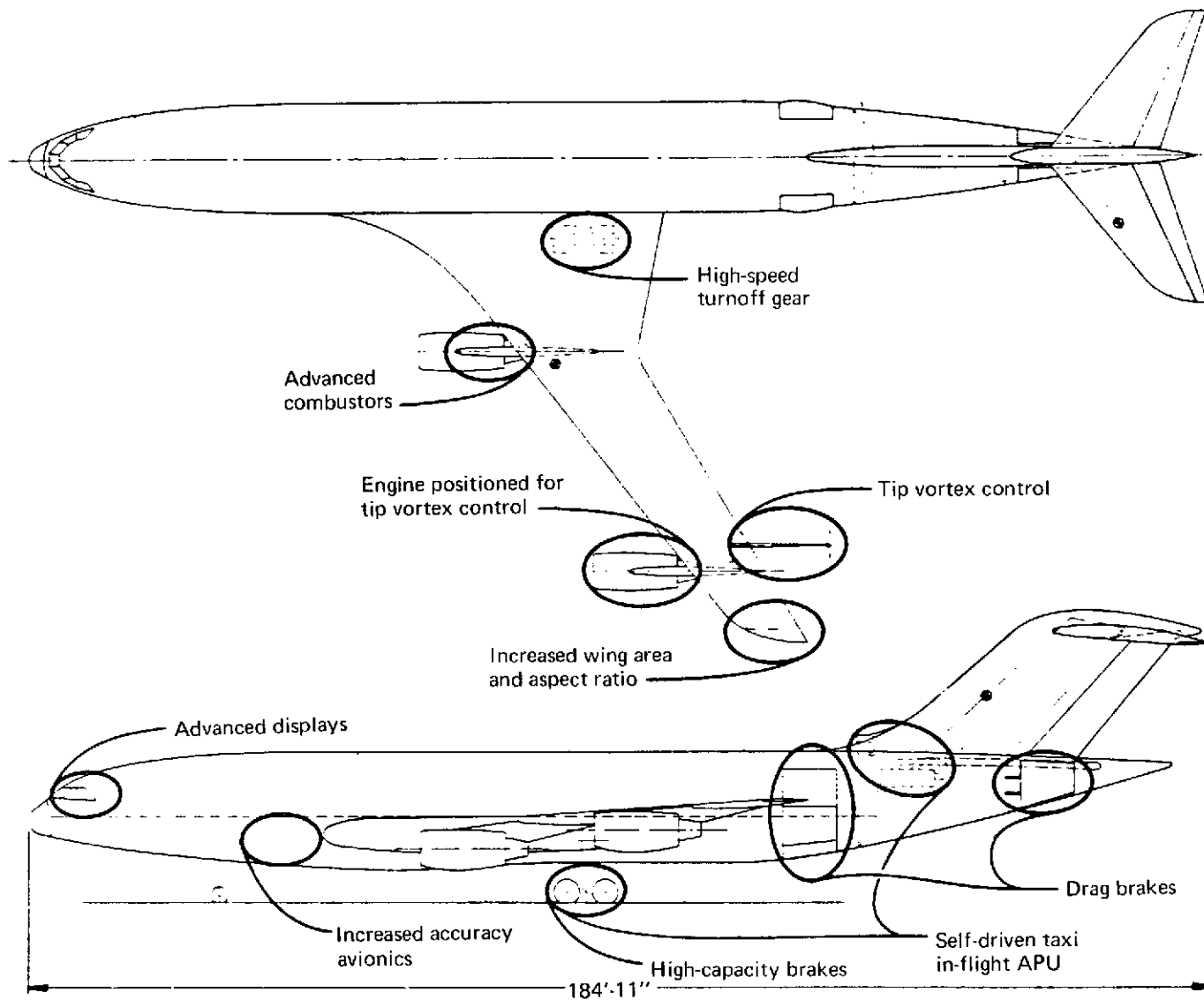


FIGURE 5.—MODIFICATIONS MADE FOR TERMINAL COMPATIBILITY

brake life. The landing gear, including both the main gear and the nose gear, were reviewed for structural soundness to accomplish the high-speed turnoffs deemed desirable to reduce congestion.

A number of modifications were made to the airplane avionics system in several areas. Improved displays enable the pilot to perform some of the desirable operational procedures such as steep descents, passenger-tolerated high deceleration rates, and high-speed turnoffs. These advanced displays were considered necessary to keep pilot workload at levels consistent with current airplane operations. Beyond that, the navigation and guidance system of the airplane was also upgraded to provide (in conjunction with ground-based ATC equipment) an increased guidance accuracy.

In addition to the foregoing considerations, a study was made to assess the effects of providing reduced takeoff and landing (RTOL) field length capability to the TAC airplane. The intent was to provide greater flexibility for developing route structures that avoid the most congested airports. Examination of various techniques to achieve the RTOL capability showed that the use of conventional mechanical flap systems would be more cost effective than any currently known propulsive-lift concept.

The proposed work items are defined by title in the matrix of table 2. The matrix columns divide technology recommendations by the functions just described, whereas the rows indicate the parts of the air transportation system affected: airplane, ground facilities, passenger, and community.

## **2.2 CATEGORIZATION BY TERMINAL-COMPATIBLE BENEFITS**

The terminal-compatible airplane was designed to provide improved congestion, noise, and emission characteristics for those airplane operations occurring in areas surrounding major airports. A summary of the improvements in these characteristics in terms of both airport impact and individual airplane qualities is given in figure 4. The number and costs of the recommended research efforts are summarized in figure 6 in terms of terminal-compatible features. Where a research item appears in two or three columns, representing benefits in more than one category, the cost is divided among the categories.

Improved airplane qualities considered in this study are rational projections assuming extensive research effort. In the absence of research and technology expenditures, the projections shown have no basis whatsoever.

TABLE 2.—PRINCIPAL R&T RECOMMENDED WORK PACKAGES

Item	Approach	Ground operations	Takeoff	Cruise
Airplane	1 Wing trailing vortex research 2 Airframe noise research and control 3 Aerodynamic drag device development 4 In-flight thrust reversers 5 Landing guidance 6 Improved anti-icing techniques 7 Impact of turbulence and wind shear on airplane design 8 Noise-abatement approach and landing study 9 Stopping system trades 10 Noise treatment versus noise abatement procedures 11 Engine component noise research 12 Engine noise reduction with lining/treatment	16 Engine emission control 17 Auxiliary power unit development 18 Tire technology 19 Landing gear/brake dynamics 20 Automated stopping system 21 Brake material and configuration 22 Ground steering systems 23 Reduced gate-space design techniques 24 Airframe and engine maintainability 25 Large payload airplane scheduling/marketing assessment 26 Aircraft maintenance monitor 27 Powered-wheel system 28 Innovating landing gear concepts 29 Powered-wheel operational assessment	38 Reduced penalty high-lift and low-noise concepts 39 Advanced, low-noise engine cycles 40 Water injection systems	41 Low cost inertial systems 42 VLF navigation 43 Impact of cruise Mach constraint 44 Structural implications of outboard engine location 45 Weight implications of high aspect ratio wings 46 Guidance and control integration 47 Secondary power system redundancy 48 Airplane design/energy relationship 49 Innovative airplane concepts for TAC application 50 Advanced fuel airplane concepts (liq. H <sub>2</sub> )
Ground facilities	13 Steep approach operational compatibility	30 Surface traffic control		
Passenger	14 Passenger compartment and flight deck noise	31 Passenger tolerances 32 Schedule-spreading incentives 33 Aircraft interior improvements		51 Cabin and interior noise, effect of M <sub>CR</sub>
Community	15 Post-1985 noise criteria	34 Ambient air quality standards review and assessment 35 Terminal area air pollution model 36 Terminal area meteorology model 37 Pollution containment altitude		

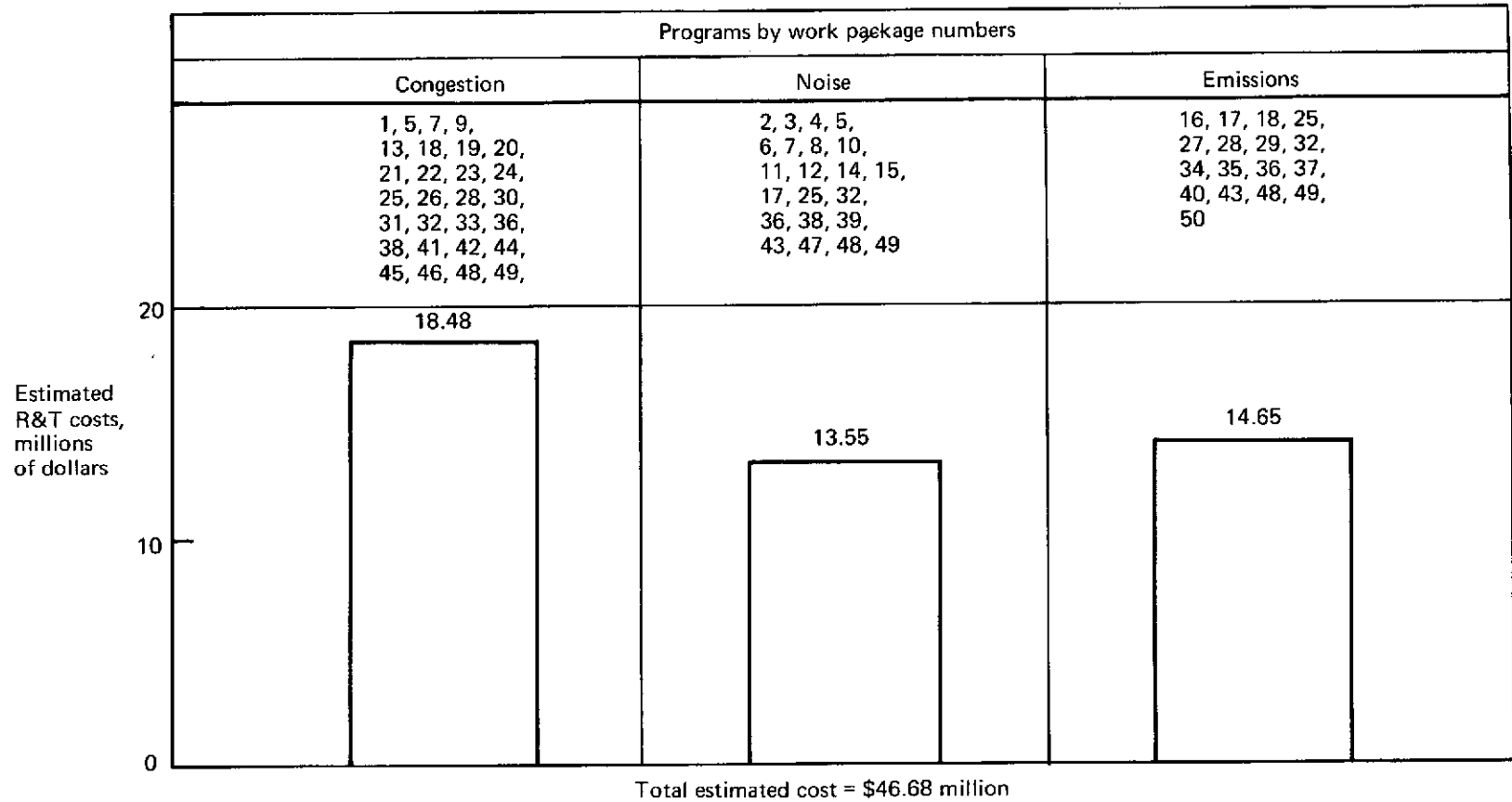


FIGURE 6.—R&T COSTS SUMMARIZED BY TERMINAL-COMPATIBILITY BENEFITS

## 2.3 CROSS CATEGORIZATION OF RECOMMENDED RESEARCH AND TECHNOLOGY

Each recommended program is primarily related to an engineering discipline such as aerodynamics, propulsion, etc. While few studies would be such that assistance from other disciplines would not be required, the recommended studies can be categorized by the discipline that is primarily involved. Table 3 indicates, by research item number (see table 2), the engineering discipline that would have primary responsibility for a particular research item. The research items are further divided to indicate the category of benefit being studied: congestion reduction, noise abatement, or emission control. For example, item 1 of table 2, "tip vortex research," is primarily an aerodynamic research project and will have a payoff in the congestion-reduction category.

Figure 7 indicates the airplane components that will primarily be impacted by each research recommendation. Research will, of necessity, include effects on other airplane components but will primarily impact the component indicated on the chart.

The matrix in table 4 is similar to that of table 2, differing in that key research programs have been highlighted by topic as well as function and affected portion of the system. Only the titles of the most important programs are shown, with others indicated by parallel lines.

**TABLE 3.—RESEARCH AND DEVELOPMENT PROGRAMS  
CATEGORIZED BY TECHNOLOGY**

Technology	Congestion	Noise	Emissions
Aerodynamics	1, 9, 48, 49	8, 38, 43, 48, 49	48, 49
Propulsion	24, 48, 49	2, 4, 10, 11, 12, 14, 15, 38, 39, 48, 49	16, 29, 34, 35, 36, 37, 40, 48, 49, 50
Noise and emissions			
Structures	3, 21, 44, 45, 48, 49	48, 49	28, 48, 49, 50
Flight controls		3, 7	
Configurations	3, 23, 25, 31, 32, 33, 48, 49	48, 49	48, 49, 50
Design			
Marketing and economics			
Human factors			
Systems	5, 13, 18, 19, 20, 22, 26, 30, 41, 42, 46	6, 47	17, 27, 28
Avionics			
Secondary power			



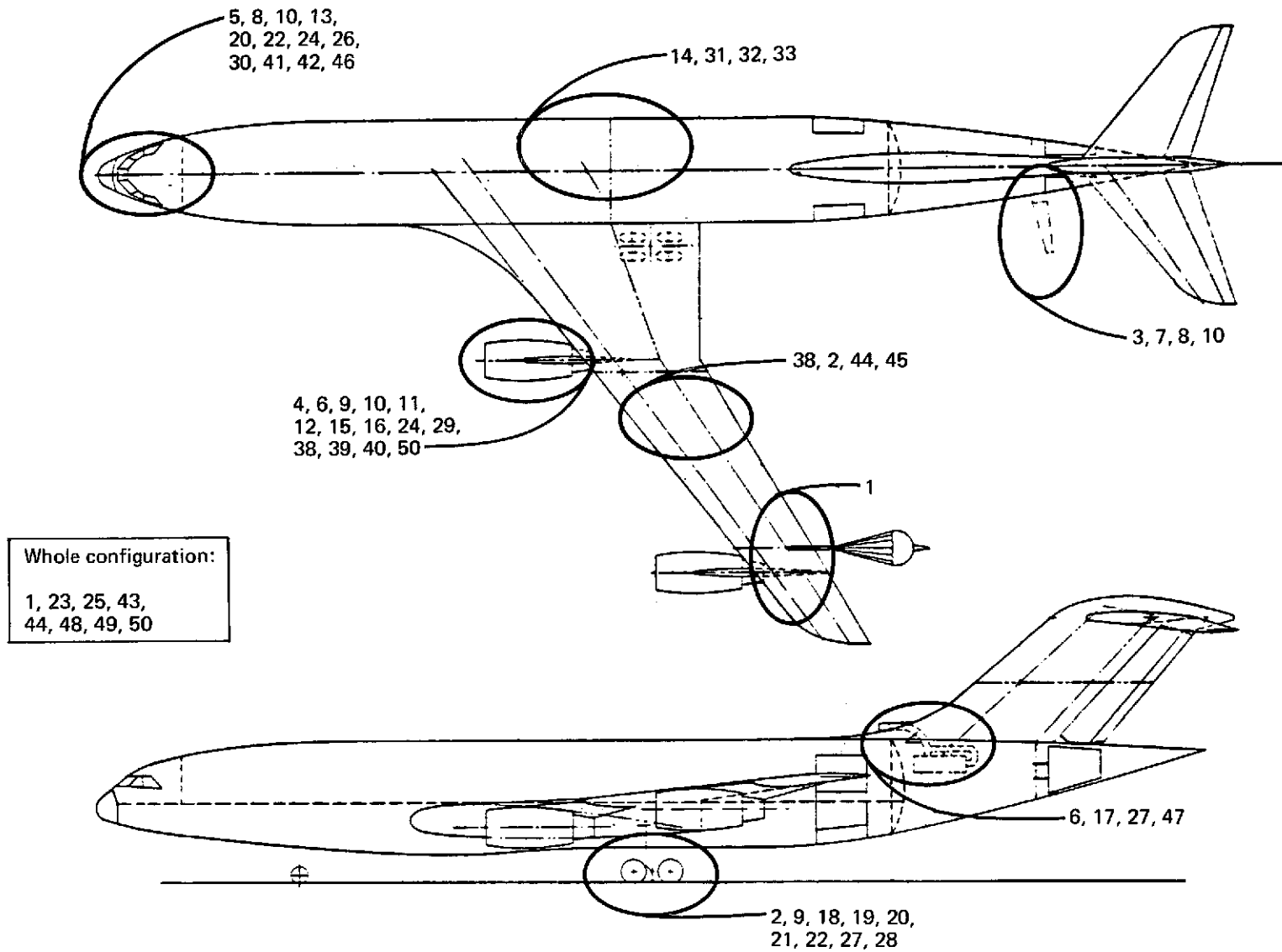


FIGURE 7.—RESEARCH AND TECHNOLOGY PROGRAMS CATEGORIZED BY AIRCRAFT COMPONENT

TABLE 4.—RESEARCH AND TECHNOLOGY PROGRAMS CATEGORIZED BY AIR TRANSPORT FUNCTION

Item	Approach	Ground	Takeoff	Cruise
Airplane	<ul style="list-style-type: none"> <li>• _____</li> <li>• Drag devices</li> <li>• Tip vortex</li> <li>• Airframe noise</li> <li>• _____</li> <li>• Landing guidance</li> <li>• Noise/procedures trades</li> </ul>	<ul style="list-style-type: none"> <li>• _____</li> <li>• _____</li> <li>• All weather ground operation</li> <li>• Low power engine emissions</li> <li>• Reduced turnaround time</li> </ul>	<ul style="list-style-type: none"> <li>• _____</li> <li>• Low penalty high-lift concepts</li> <li>• _____</li> <li>• _____</li> <li>• Advanced low-noise engine cycles</li> <li>• _____</li> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• Outboard engine integration</li> <li>• _____</li> <li>• Cruise Mach number</li> <li>• Reduced-fuel airplane</li> <li>• Advanced configuration concepts</li> <li>• _____</li> </ul>
Ground facilities	<ul style="list-style-type: none"> <li>• Steep approach/ATC compatibility</li> <li>• _____</li> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• _____</li> <li>• Surface traffic mgmt</li> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• _____</li> <li>• _____</li> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• _____</li> <li>• _____</li> </ul>
Passenger	<ul style="list-style-type: none"> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• Tolerance studies</li> <li>• _____</li> <li>• Schedule spreading</li> <li>• _____</li> <li>• _____</li> </ul>		<ul style="list-style-type: none"> <li>• In-flight APU</li> </ul>
Community	<ul style="list-style-type: none"> <li>• Community noise criteria</li> <li>• _____</li> <li>• _____</li> </ul>	<ul style="list-style-type: none"> <li>• Ambient air quality</li> <li>• _____</li> <li>• Meteorology</li> </ul>		

## **2.4 RELATIONSHIP TO PREVIOUS ATT PROGRAM RECOMMENDATIONS**

The ATT study provided the baseline airplane for the TAC program and also resulted in an extensive list of needed research, which is documented in reference 2. Some of the items listed were found to be important to terminal-area compatibility, so they are repeated, in updated or modified form, in this report. Many of the other ATT research recommendations, not specifically connected with terminal-area problems, are still regarded as important research objectives. This is because efficiency improvements through all aircraft technologies must be continually sought to help offset the costs imposed by environmental constraints. The ATT research recommendations (ref. 2), 95% of which are judged to be consistent with terminal-area compatibility objectives, are discussed briefly below under the headings of the ATT report.

### **2.4.1 Design Integration**

Due to budget limitations, the TAC program could only do a first cycle of integration of individual features into a complete configuration. The ATT recommendation for continued overall configuration studies to achieve the best compromise among safety, economic, and environmental goals becomes even more important when the TAC features are included. Both incremental variations and entirely novel approaches are needed. Design for lower maintenance costs and delays are a continuing economic need; major improvements in airplane reliability could be more significant to the air transportation industry than modest aerodynamic or propulsion technology advances.

Increased reliance on sophisticated avionics must be offset by cost reductions and reliability improvements achieved through system integration and advanced technology.

### **2.4.2 Aerodynamic Configuration**

The research on more efficient airfoils and configurations is always needed but is especially important in terms of helping to improve the overall payload to gross weight fraction of the airplane. This efficiency improvement provides less noise, emissions, and congestion per passenger-mile.

### **2.4.3 Structures and Materials**

The search for lighter structure, both through composite materials and active controls, is made more urgent by the TAC features that exact weight penalties.

#### **2.4.4 Power Systems**

The TAC study has reemphasized the need for development of quieter, more emission-free engines. The broader ATT recommendations, including integration of advanced engines with nacelles and with complete airplane configurations, is necessary to realize the full benefit from the improved engines. The need for reduced weight and greater reliability throughout the secondary power systems remains important.

#### **2.4.5 Control of Flight**

The TAC goals could only be met because the flight control and navigation/guidance systems were assumed to have the advanced characteristics that will result from the ATT-recommended research. This research is still essential.

#### **2.4.6 General**

In all technical areas, the previous ATT recommendations included development of better analysis and prediction capability through model development and model verification tests. This is a continuing need; better prediction allows less unnecessary conservatism in design and gives greater freedom for novel approaches such as some of the TAC features. Figures 8 and 9 reproduce the summary cost and schedule requirements determined under the ATT program. Note the considerable expense and effort estimated to bring research concepts to the state of readiness required prior to manufacturer commitment to a commercial transport program.

### **2.5 POTENTIAL ECONOMIC BENEFITS**

In addition to the large economic savings and social benefits to the community, volume I gives details of the tangible economic benefits associated with delay reduction. The TAC modifications to accomplish these benefits and the costs incurred are also discussed in volume I. Figure 10 expands the expected benefits from the calculated direct operating costs on a dollars-per-airplane-mile basis to the total saving on a fleet of 300 TAC-type aircraft over a 14-year life of the aircraft involved. A total benefit of over \$1 billion in reduced direct operating costs is forecast if the technology advances can reduce delay to 6 min. Indirect costs are not included but will also be reduced by reduced delay.

The estimated research and technology costs (\$46.68 million) are shown on the same chart. They are a small fraction of the potential payoff. It is important to note several facts concerning the data in figure 10.

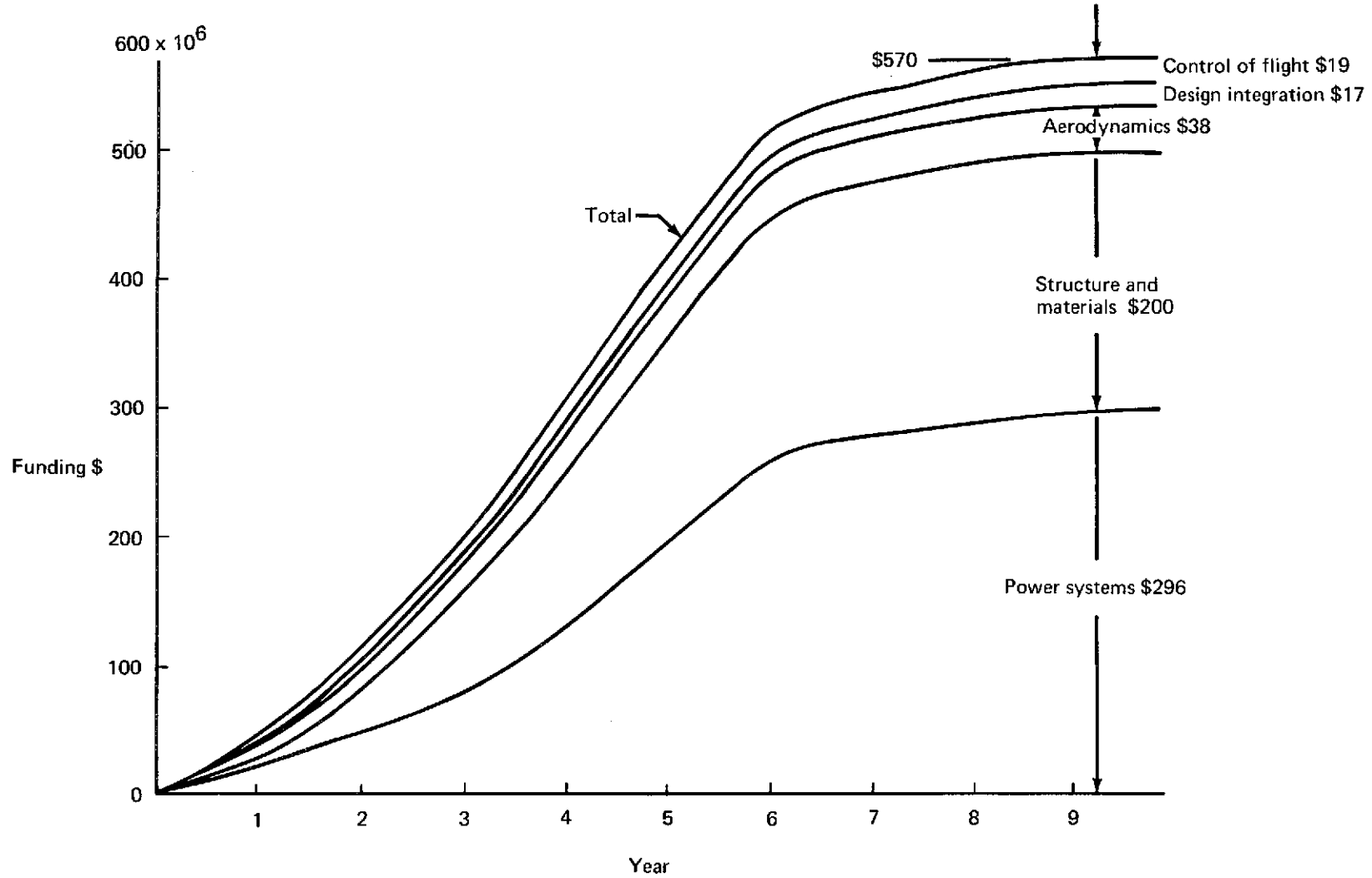


FIGURE 8.—RECOMMENDED RESEARCH AND TECHNOLOGY BASED ON ATT STUDIES

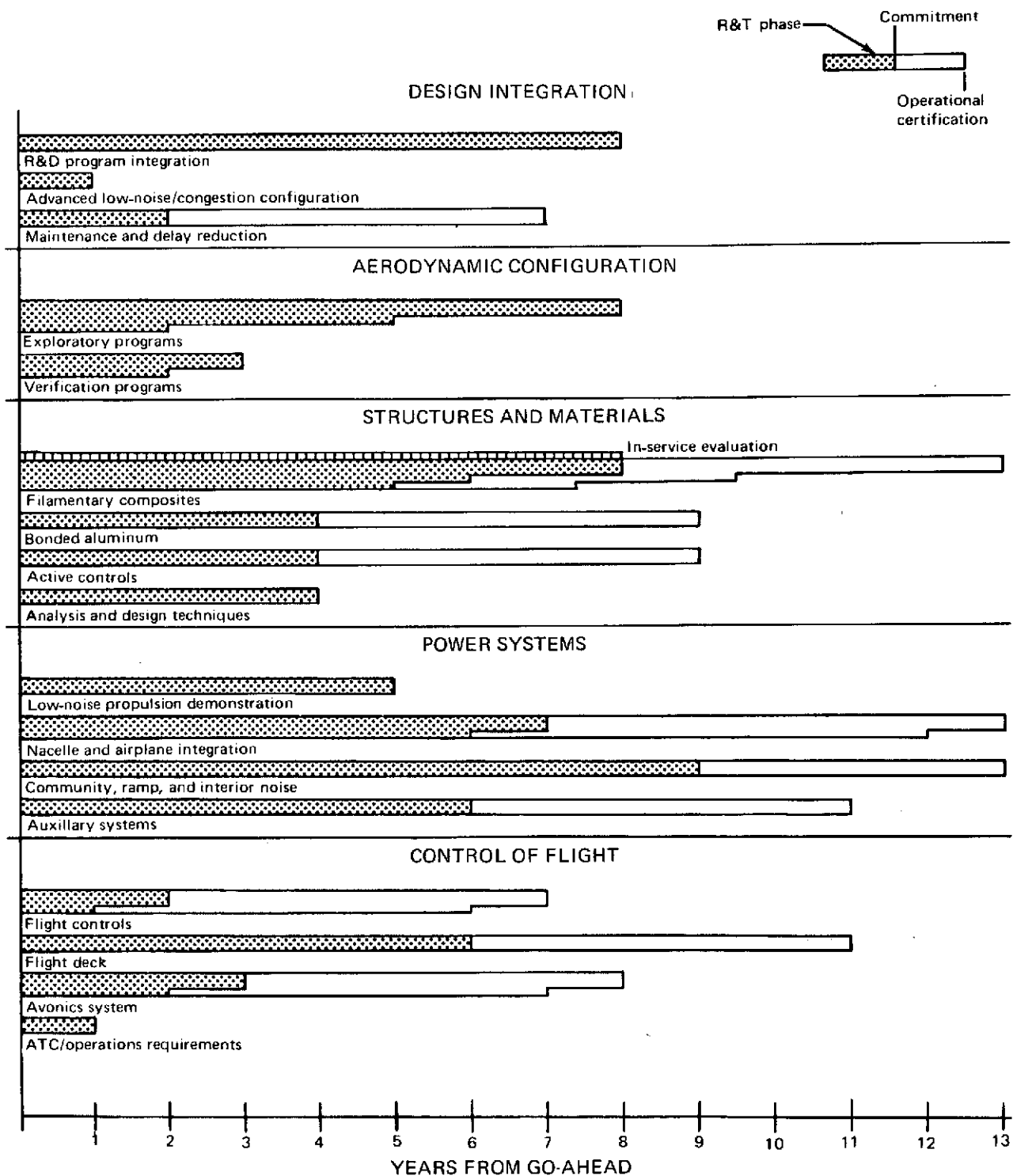


FIGURE 9.—ADVANCED TECHNOLOGY PROGRAM RECOMMENDATIONS  
BASED ON ATT STUDIES

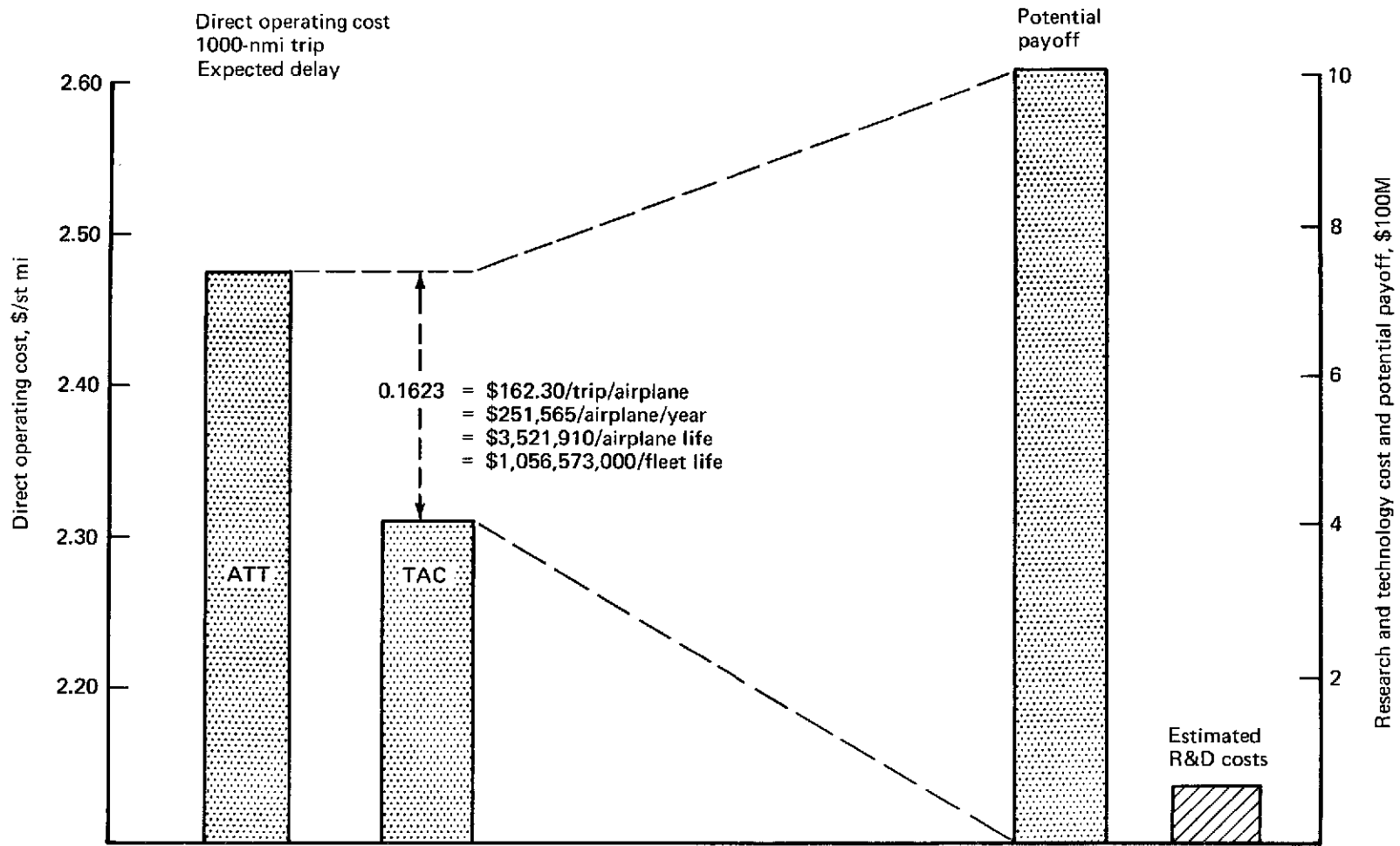


FIGURE 10.—ECONOMIC IMPACT OF RESEARCH AND TECHNOLOGY PROGRAMS

- a) The reduced TAC operating costs on the left side of the figure are a result only of savings achieved by congestion reduction.
- b) The TAC operating costs already include penalties for not only the congestion design modifications, but also for those associated with noise and pollution reduction.
- c) The potential payoff shown on the right hand side of the figure is, again, an accounting only of benefits derived by reduced delay. The environmental benefits of noise and pollution reduction, if capable of expression in monetary terms, would be additive to those of reduced delay.
- d) The estimated R&T costs shown on the right side of the figure include not only congestion, but also noise and emission technology programs.



### 3.0 SYMBOLS AND ABBREVIATIONS

ADS	air data system
AFCS	automatic flight control system
alt	altimeter
App	approach
APU	auxiliary power unit
ASDE	airport surface detection equipment
ATC	air traffic control
ATT	advanced transport technology
CAS	collision-avoidance system
CO	carbon monoxide
comm	communications
CRT	cathode ray tube
CTOL	conventional takeoff and landing
CWB	current widebody
dB	decibel
DCA	Washington National Airport
DLC	direct lift control
DOC	direct operating cost

DOT	Department of Transportation
EADI	electronic attitude director indicator
EPA	Environmental Protection Agency
EPNdB	effective perceived noise decibels
EPNL	effective perceived noise level
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
fps <sup>2</sup>	feet per second per second
G&C	guidance and control
GW	gross weight
HC	hydrocarbons
hr	hour
Hz	hertz
H <sub>2</sub>	hydrogen
ILS	instrument landing system
ISS	inertial sensor system
JFK	John F. Kennedy Airport
kg	kilogram
km	kilometer
kn	knots

LAMS	load alleviation and modal suppression
LAX	Los Angeles International Airport
lb	pound
LH <sub>2</sub>	liquid hydrogen
m	meter
M	Mach
M <sub>CR</sub>	cruise Mach number
mech	mechanical
MFD	multifunction display
MLS	microwave landing system
m/sec <sup>2</sup>	meters per second per second
NAAQS	national ambient air quality standards
nmi	nautical mile
no.	number
NO <sub>x</sub>	nitrogen oxides
NPV	net present value
ORD	O'Hare Airport
$\dot{P}$	roll acceleration
periph	peripheral
PNdB	perceived noise decibels

PL	payload
PND	pictorial navigation display
PWI	proximity warning indicator
Q	source emissions
R	ring
R&D	research and development
R&T	research and technology
RNAV	area navigation
RSFS	research support flight system
RTOL	reduced takeoff and landing
S	splitter
SAS	stability augmentation system
sec	second
SFO	San Francisco Airport
SL	sea level
SLC	Salt Lake City Airport
SST	supersonic transport
st mi	statute mile
TAC	terminal-area compatibility
TAI	thermal anti-icing

TCV	terminal-configured vehicle
T.O.	takeoff
TOGW	takeoff gross weight
u	wind velocity
VLF	very low frequency
W/R	weather radar
X	air quality concentration
$\delta_{\max}$	maximum aileron deflection
$\Delta$	increment
$\sigma_y$	standard deviation, horizontal
$\sigma_z$	standard deviation, vertical
	degree

## **4.0 DETAILED PROGRAM RECOMMENDATIONS**

Fifty recommended research packages are listed in this section, grouped by the appropriate phase of flight. In many cases, this grouping is somewhat arbitrary, since some developments are useful to more than one flight phase. The recommended research includes both work directly needed to achieve the airplane capability indicated as desirable by the study and work needed to fill gaps in essential knowledge uncovered during the study.

For each research item, the potential payoff, the current state of readiness, and the recommended action are listed. An estimate of the magnitude of the cost and duration of each item is included; more precise costs and schedules, the extent to which these items could be combined with each other or with other research programs, and the relative timing of the various items would require further study.

### **4.1 RESEARCH AND TECHNOLOGY AFFECTING APPROACH**

The major areas of concern on approach and landing are the noise footprint near the approach path and the ability to fly the string of arriving airplanes closely spaced for maximum system flow capacity. The research items in this section are related to these problems (see fig. 11).

#### **4.1.1 Work Package 1—Wing Trailing Vortex**

##### **4.1.1.1 Potential Payoff**

Solution of the wingtip vortex problem will allow operation of aircraft at their optimum spacing for minimum congestion and delay and reduce the hazard to general-aviation-type small aircraft that penetrate the region in which the larger airplane has flown (see figs. 12 and 13). The demand now exceeds the capacity of major airports an appreciable fraction of the time and is steadily increasing. Several-fold increases in capacity can be achieved by joint development of airports, ATC, and airplanes; if the trailing vortex problem cannot be solved, only slight capacity increases can be achieved by improvement to the rest of the system.

##### **4.1.1.2 State of Readiness**

Fundamental research into the trailing vortex problem is now in its eighth decade of activity, but at this time no solution has been verified for the vortex problem. The basic physics of vortices is understood, but the detailed relationship between airplane and atmospheric parameters and the

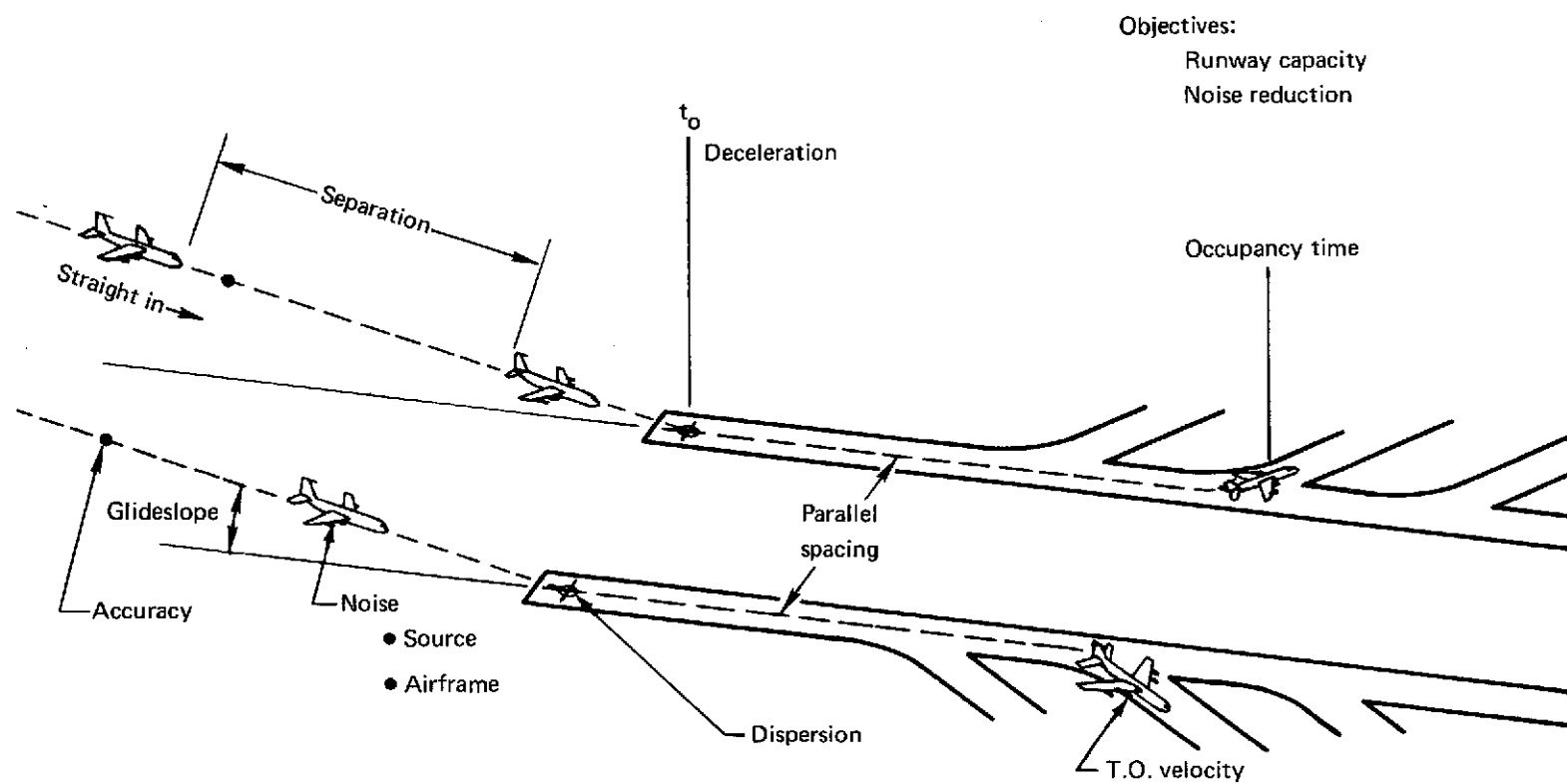


FIGURE 11.—RESEARCH AND TECHNOLOGY AFFECTING APPROACH OPERATIONS

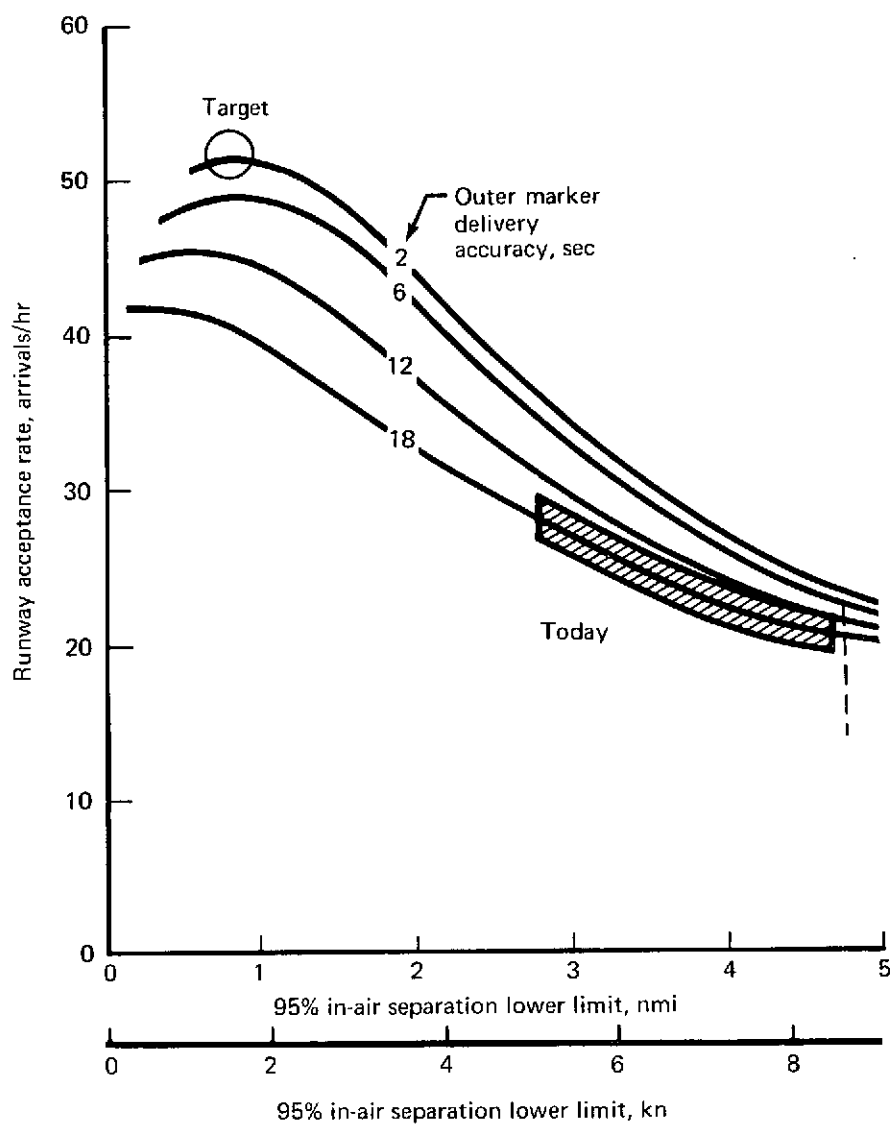


FIGURE 12.—MOTIVATION FOR WING TRAILING VORTEX SOLUTION

stability of vortex formation and persistence is not well established. Based on broad theoretical models, vortex dissipation methods have been proposed, and promising qualitative test results have been obtained.

#### 4.1.1.3 Recommended Action

A multiphase program is proposed that aims at solving the wing trailing vortex problem. The initial phases of the program would be directed toward understanding the formation of the vortex system, surveying the encounter probability, establishing detection techniques that lead to



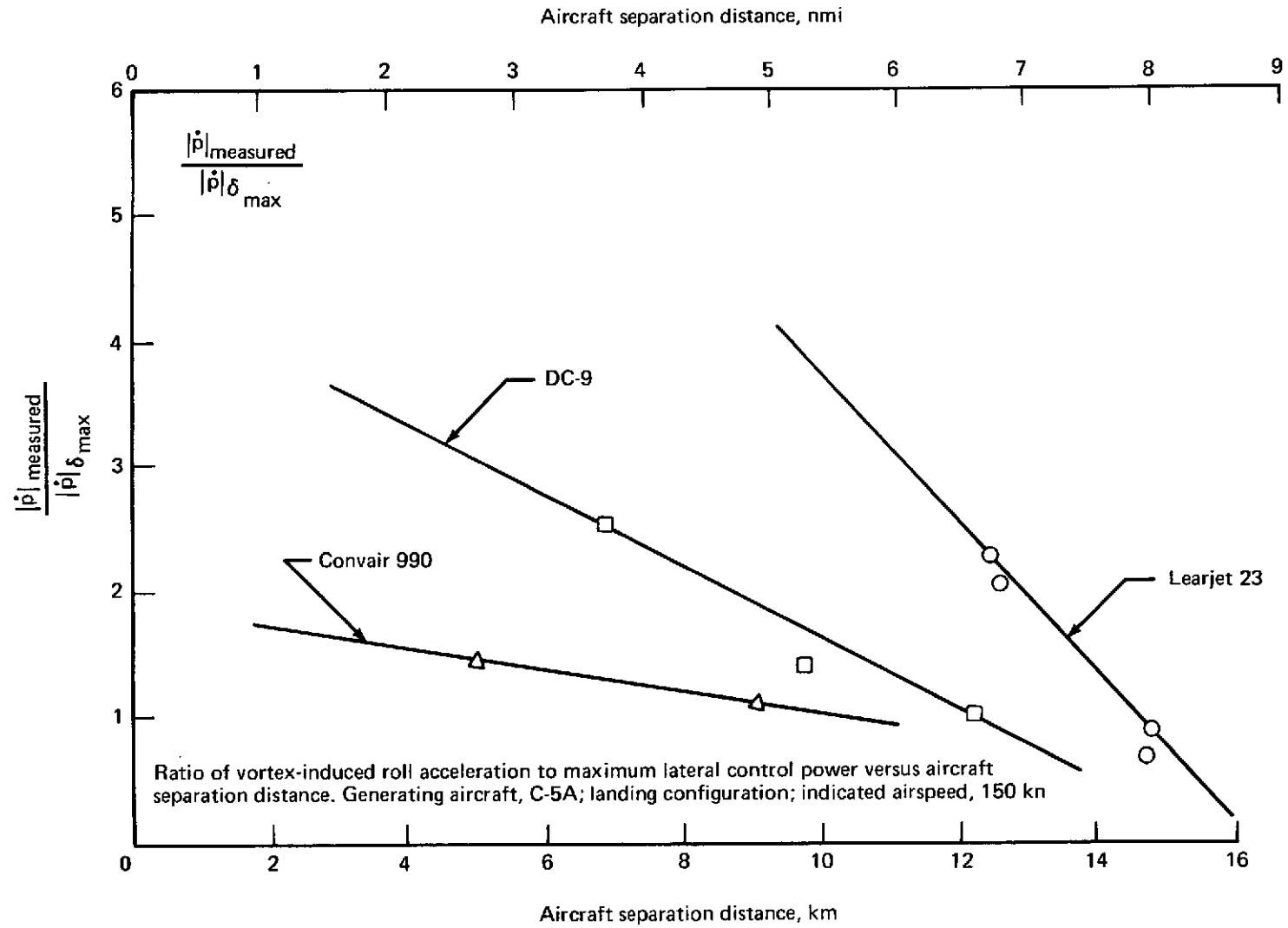


FIGURE 13.—EFFECT OF WING TRAILING VORTEX STRENGTH ON FOLLOWING AIRCRAFT

avoidance procedures, and increasing knowledge of effects on following airplanes as a function of meteorological conditions and following airplane design. The flight tests would verify the sensitivity and reliability of prediction logic and detection systems and the hazard if a vortex system were encountered. The use of different flightpaths to the same runway for heavy and light aircraft would be considered.

The second phase would evaluate the effectiveness of various devices in dissipating aircraft trailing vortices or find means of discouraging vortex formation. (A 1-year program to evaluate the various devices proposed for enhancing vortex decay and extrapolation of laboratory results to full scale has been funded by NASA.)

The third phase would flight demonstrate the vortex dissipating devices.

#### **4.1.1.4 Cost and Schedule**

It is recommended that the program (fig. 14) be funded at an approximate cost of \$1 to \$1.5 million per year for the basic research and \$2 to \$5 million per year for the applied research phases. It is not possible without a definition of the wing trailing vortex dissipator to assess the cost of the flight demonstration phase of this program.

### **4.1.2 Work Package 2—Airframe Noise Research and Control**

#### **4.1.2.1 Potential Payoff**

The reduction of airframe noise can potentially provide a 3- to 5-EPNdB aircraft noise reduction during landing. A 3-EPNdB reduction is equivalent to a 30% reduction of the area enclosed by 90 EPNdB during a 3° glideslope approach. To achieve this reduction, engine noise sources must be reduced below the airframe noise level. The impact of airframe noise as source noise is reduced is shown in figure 15. The reduction of airframe noise when combined with 6°/3° or 9°/3° two-segment landings provides less benefits. A 10% reduction in the 90-EPNdB area can be expected under these landings.

Airframe noise reduction has an especially large benefit when an aircraft is occasionally forced to make low-altitude approaches because of combinations of weather and equipment failures.

#### **4.1.2.2 State of Readiness**

Airframe noise investigations are being conducted to relate airframe noise to aircraft design and operational characteristics. Several candidates for reducing airframe noise have been postulated. Examples are:

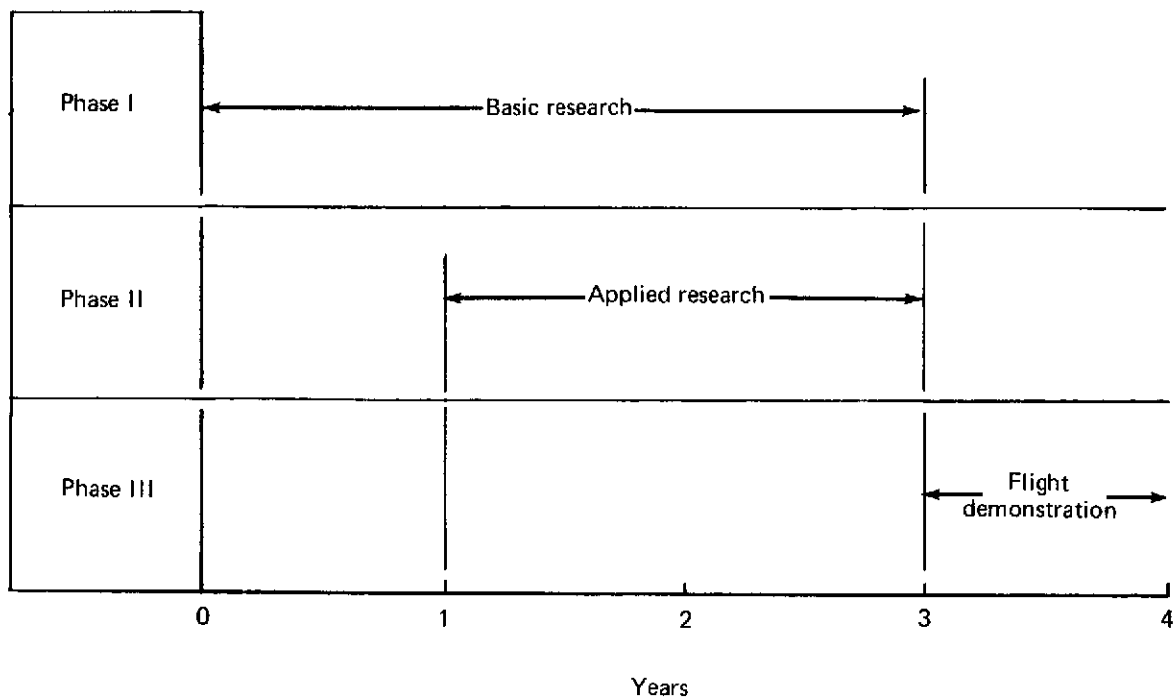
### WORK STATEMENT

- Understand vortex formation
- Develop detection techniques
- Define encounter probability
- Demonstrate flightpath control for avoidance techniques
- Develop dissipation devices or techniques
- Model test evaluation and verification
- Flight test verification

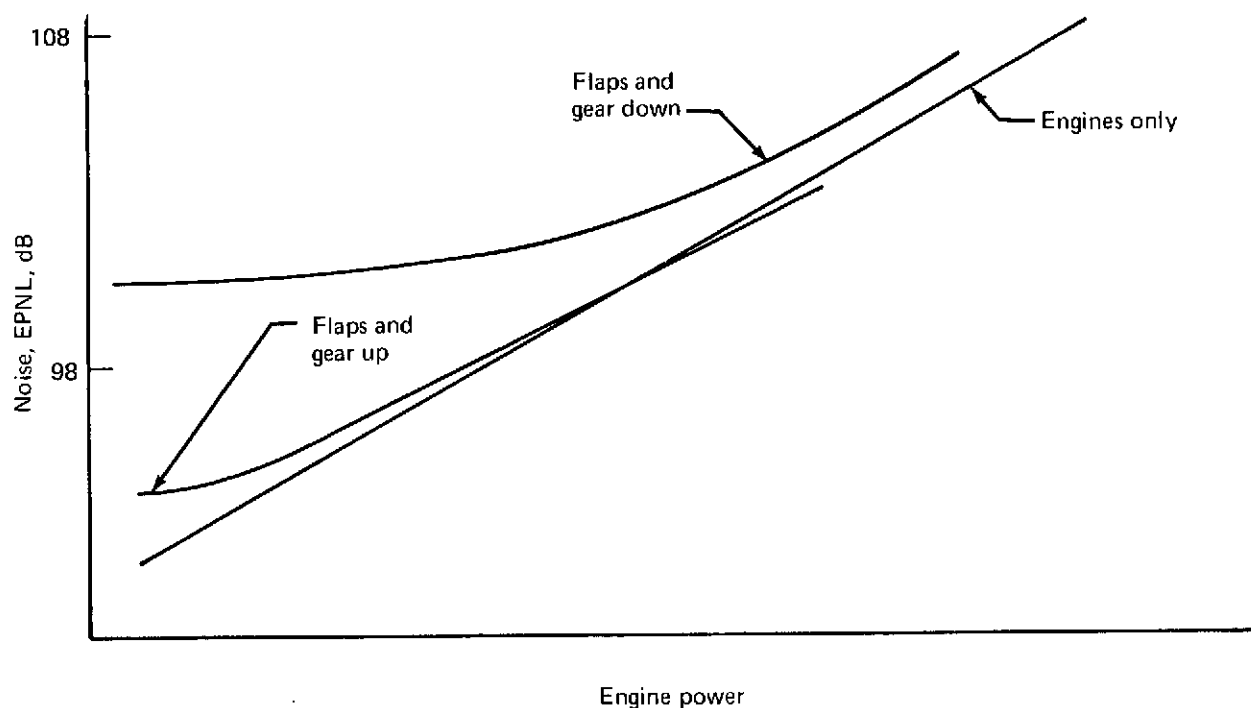
### PAYOFF

- Reduced congestion
- Improved safety

### SCHEDULE



*FIGURE 14.—WING TRAILING VORTEX  
RESEARCH AND TECHNOLOGY SUMMARY*



**FIGURE 15.—AIRFRAME/ENGINE—APPROACH NOISE**

- a) Fairings for landing gear struts and/or wheels
- b) Doors to close wheel well cavities during approach
- c) Various laminar-flow devices and turbulence-reduction schemes
- d) Fairings to surfaces for housing antennas, flap brackets, landing gear, and other projections.

An accelerated program of noise research, to include testing, is needed in the areas listed above if the tools for reducing airframe noise are to be available for a 1985 terminal-compatible aircraft.

#### 4.1.2.3 Recommended Action

A four-part program combining the aerodynamic, propulsion, and noise disciplines is recommended.

- a) Part I—theoretical analysis and facility survey
- b) Part II—scale model component experiments

- c) Part III—flight testing of promising concepts
- d) Part IV—design recommendations

#### 4.1.2.4 Cost and Schedule

The 2-year program (fig. 16) is estimated to require \$700,000.

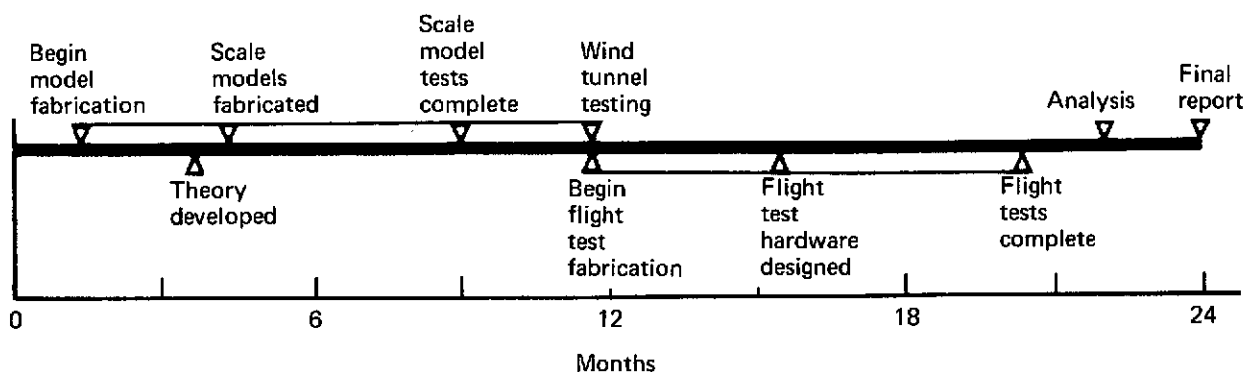
##### WORK STATEMENT

- Conduct theoretical analysis and facility survey
- Conduct scale model component experiments
- Conduct flight testing of promising concepts
- Provide design recommendations for low airframe noise

##### PAYOFF

- Reduced landing noise

##### SCHEDULE



**FIGURE 16.—AIRFRAME NOISE RESEARCH AND CONTROL**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.1.3 Work Package 3—Aerodynamic Drag Device Development

##### 4.1.3.1 Potential Payoff

The desire to reduce community area noise led to the incorporation of aerodynamic drag devices on the TAC airplane, as shown in figure 17, to implement noise-abatement landing approaches. For example, the TAC airplane can reduce centerline source noise 10 EPNdB 20,000 ft from the runway end by using a two-segment glideslope approach procedure transitioning from a 9° upper glideslope to a 3° lower glideslope at 152 m (500 ft) altitude. To implement this two-segment approach, additional aerodynamic drag is needed on the 9° glideslope on the order of 66% of the

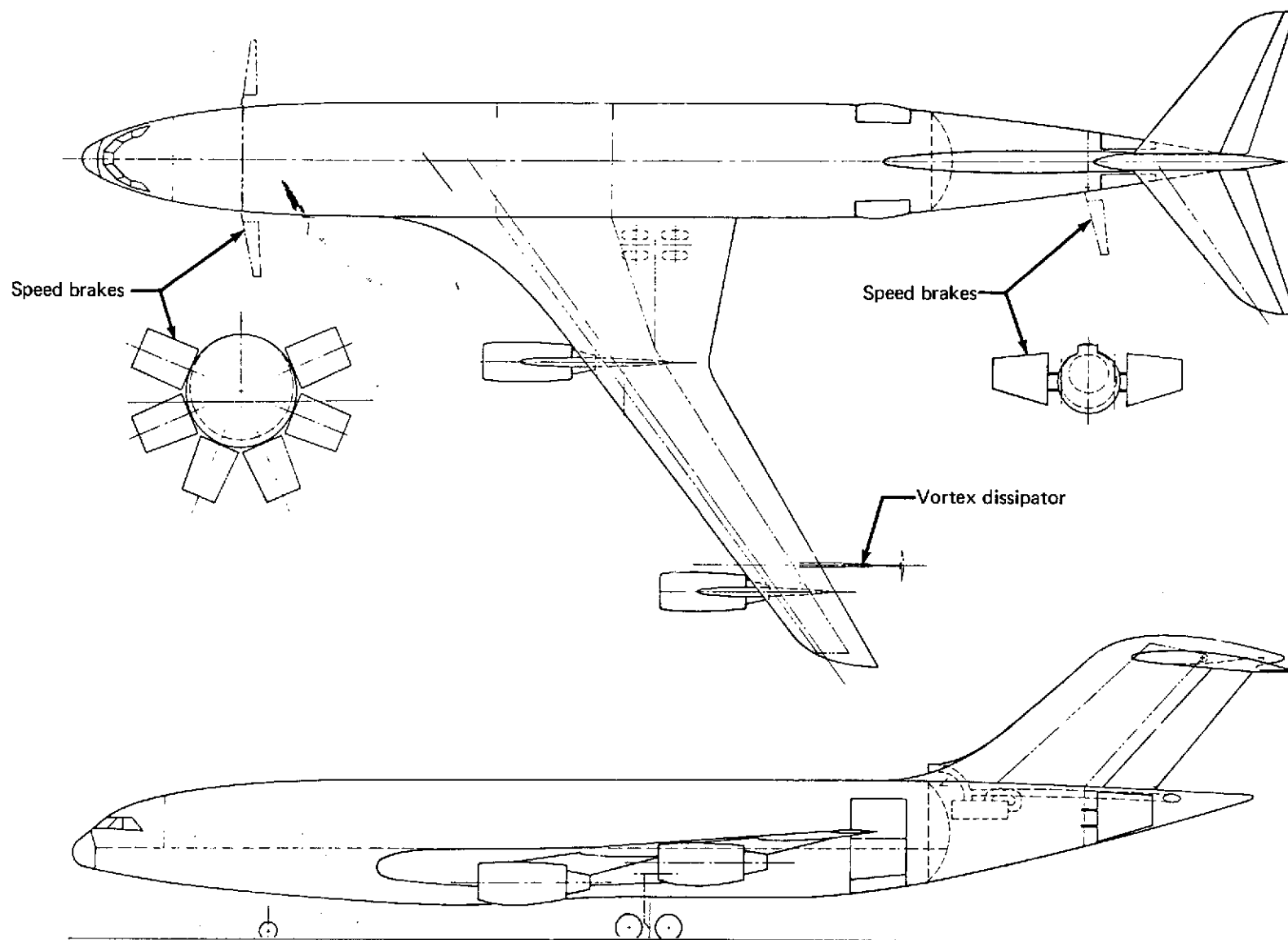


FIGURE 17.—POSSIBLE AERODYNAMIC DRAG BRAKE CONFIGURATIONS

level-flight landing configuration drag. The aerodynamic drag is required to maintain nonaccelerating flight on the 9° glideslope with an adequate margin for speed and path control in a shearing tailwind. The potential noise benefits associated with noise-abatement procedures are presently constrained by the engine minimum flight idle thrust setting (source noise limit). With the added flightpath flexibility that aerodynamic drag devices provide, possible changes in operational landing procedures will include steeper one-segment, two-segment, and decelerating approaches. This improvement in airplane capability, combined with the proposed more flexible future ATC navigation and guidance environment, will help each airport meet its specific noise and congestion goals.

#### 4.1.3.2 State of Readiness

Tail cone aerodynamic drag brakes are presently employed on the Fokker F-28, Lockheed Jetstar, and North American Sabreliner, allowing short landing performance. However, no presently operational system gives the magnitude of drag required to implement 9° glideslope approaches on large transport airplanes. Extensive use of aerodynamic drag brakes has been made with military airplanes as with the North American F-86, Convair F-106, Republic F-105, and Lockheed F-104. These available operational data could be used in the initial configuration development of aerodynamic drag brakes for larger commercial transports.

#### 4.1.3.3 Recommended Action

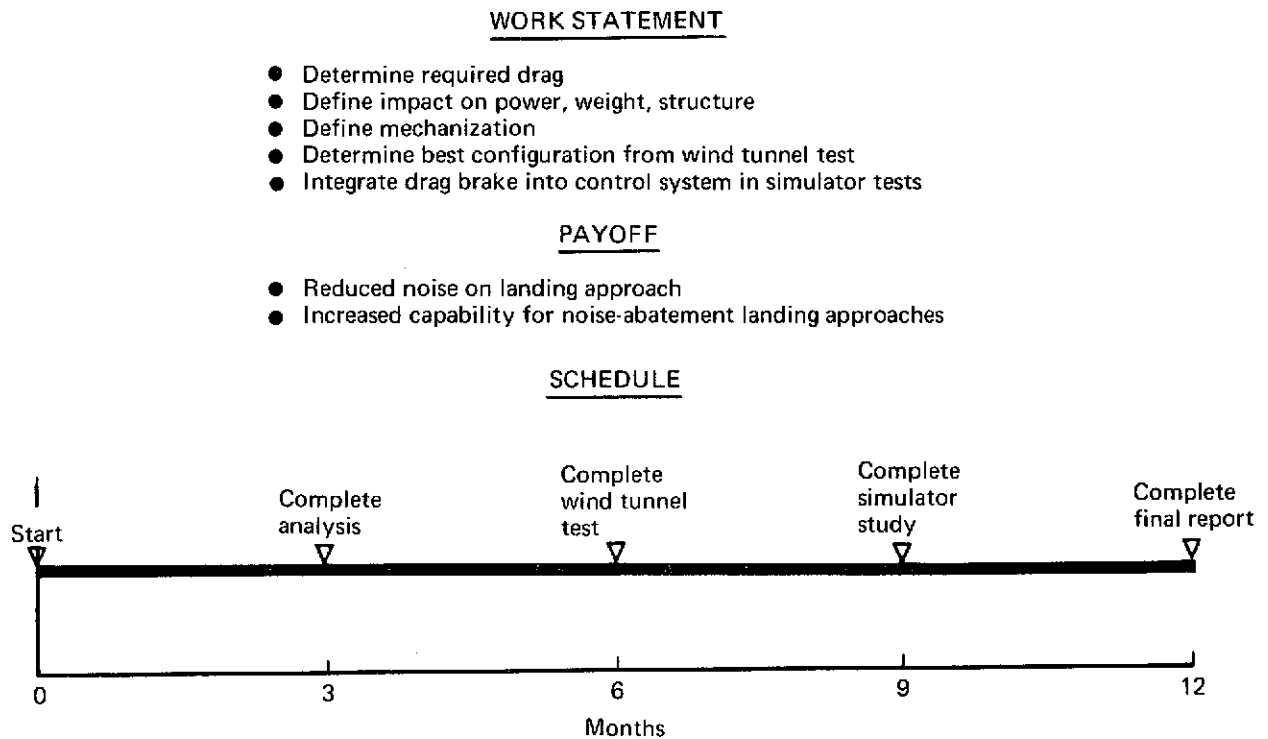
A multiple program that leads to an early in-service evaluation of aerodynamic drag brakes is recommended. Phase I would be a preliminary design and analysis effort to determine the aerodynamic drag required to implement noise-abatement landing approaches while defining the power, weight, structural, and mechanical mechanization impact. Development of an airport wind and air turbulence model suited to this study would be required.

Phase II would investigate various speed brake arrangements on different commercial transport designs in the wind tunnel. The wind tunnel testing will uncover any possible interference or buffet problems while identifying basic drag capability of these large drag devices. These tests should include wing-mounted, tail cone, aft fuselage, and mechanical parachute-type devices.

Phase III would be a simulator study to integrate the aerodynamic drag brake into the flight control system. Speed brake rate of actuation, resolution, and failure modes of operation would be established by simulating various noise-abatement landing approach procedures. In addition, the requirements for speed and flightpath control in low-altitude winds and turbulence placed on the aerodynamic drag brakes could be investigated. Later phases would include airplane modification and testing.

#### 4.1.3.4 Cost and Schedule

The 1-year program plan, shown on figure 18, is estimated to require a total funding of \$300,000.



**FIGURE 18.—AERODYNAMIC DRAG DEVICE DEVELOPMENT**

#### RESEARCH AND TECHNOLOGY SUMMARY

#### 4.1.4 Work Package 4—In-Flight Thrust Reversers

##### 4.1.4.1 Potential Payoff

An in-flight thrust reversal system would provide the airplane with a steep descent capability for noise abatement without using auxiliary drag devices. Operating the engine in reverse thrust or in a no-forward-thrust configuration would also allow higher power settings required for providing thermal anti-icing bleed and short spool-up times without jeopardizing this steep-descent capability. The trade between decreased noise due to the steeper descent and any increase of source noise due to the use of reverse thrust must be evaluated.



#### 4.1.4.2 State of Readiness

In order to have steep-descent capability, the terminal-compatible airplane had two large APUs to provide thermal anti-icing bleed requirements during approach, so the engines could be throttled down to an appropriate thrust level. The installation of large auxiliary drag devices was also required. By using an in-flight thrust reversal system, the engine could be operated at thrust levels required for providing TAI bleed while eliminating the need for the auxiliary drag devices.

Since steep descents are instituted for noise abatement, an in-flight thrust reversal system would have to be compatible with low-noise goals. This may require a variable-geometry concept.

Figure 19 presents an in-flight thrust reverser concept for a military application. Work is required to tailor such a concept for a commercial application.

#### 4.1.4.3 Recommended Action

A three-phase technology program is envisioned that will begin with in-flight thrust reverser concept design studies and supporting analysis followed by system design studies of promising thrust reverser concepts. Model-scale testing, both static and wind tunnel, would provide data to validate analytical results and provide a basis for a full-scale test demonstration.

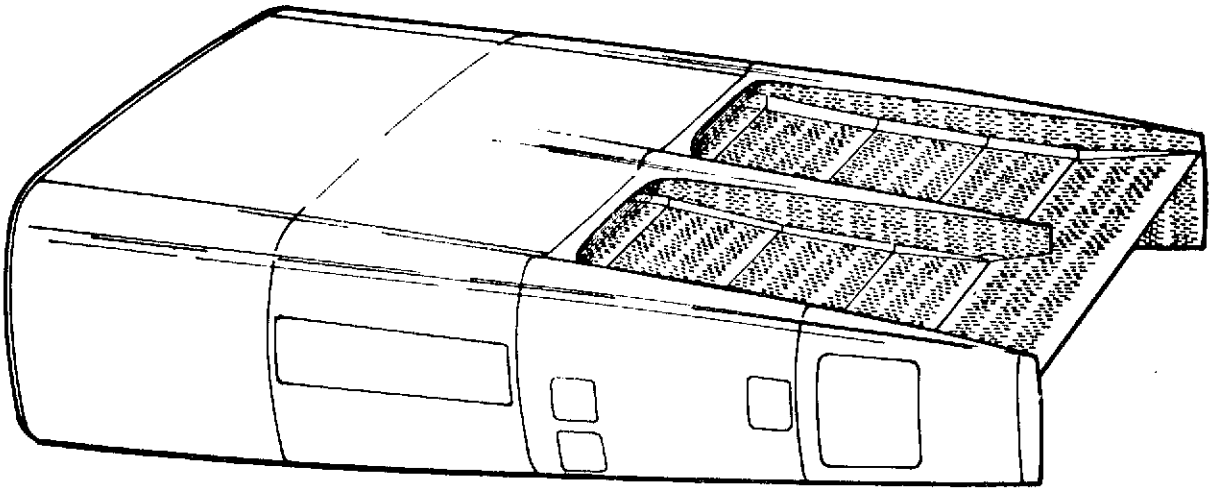
Phase I would be a conceptual design study organized as follows:

- a) Technology Review—Review previous programs, study results, and test data to assemble data needed for follow-on analysis.
- b) Conceptual Design—Conduct in-flight thrust reverser arrangement design studies around the selected engine concept. Both conventional and special-purpose thrust reverser concepts would be investigated.
- c) Math Modeling—Identify a suitable math modeling procedure and initiate modeling studies to determine the flow field and effectiveness of several conceptual designs.

Phase II would be a system design study organized as follows:

- a) Design Studies—Conduct system design studies in conjunction with a 737 airplane configuration to integrate engine and airframe.

THRUST VECTORING



THRUST REVERSING

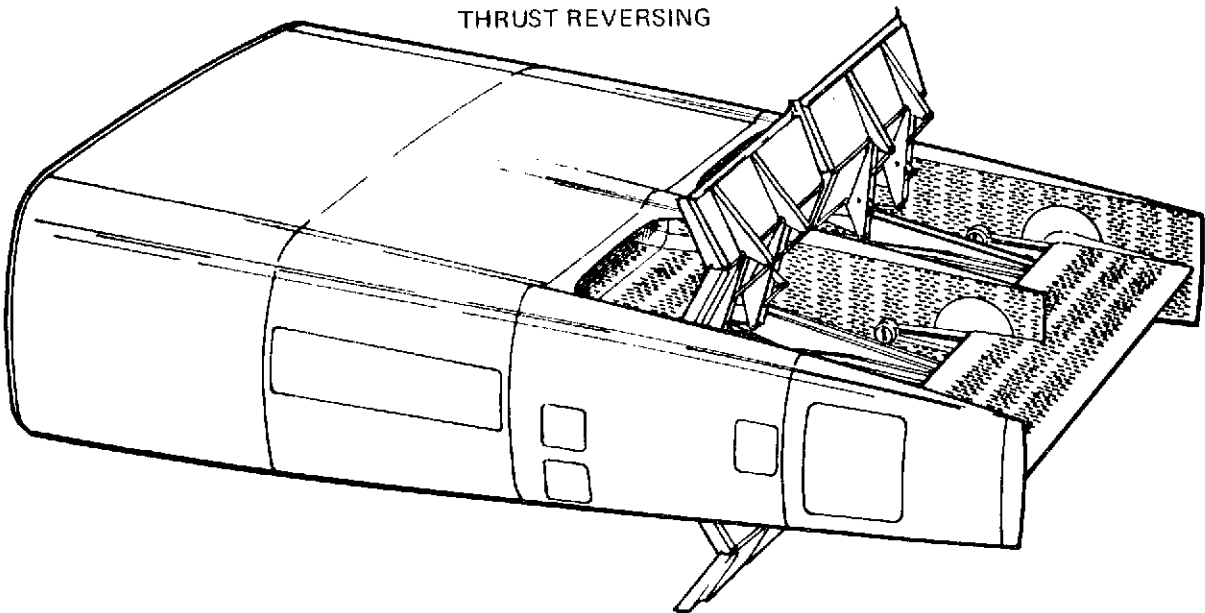


FIGURE 19.—IN-FLIGHT THRUST REVERSER CONCEPT

- b) **System Analysis**—Conduct analyses of promising configurations to identify thrust reverser effectiveness and flow stability of the engine cycle and reverser gas flow field around the airplane.

Phase III would be a demonstration test organized as follows:

- a) **Model Scale**—Wind tunnel test models of promising concepts would be constructed and static reverser and wind tunnel flow field tests conducted to verify analytical results.
- b) **Full Scale**—Based on wind tunnel results and analyses and feasibility studies of candidate thrust reverser applications for a test aircraft, design studies leading to a full-scale flight test demonstration would be conducted and demonstrated flightworthy hardware fabricated. Flight tests would be conducted to demonstrate the stability, noise, and thrust reverser effectiveness and acceleration time. This could be accomplished on a small transport such as the 737.

#### 4.1.4.4 Cost and Schedule

The 3-1/2-year program plan shown in figure 20 would require a total funding of \$1.5 million.

### 4.1.5 Work Package 5—Landing Guidance

#### 4.1.5.1 Potential Payoff

To meet the air transportation demand of the next few decades, the flow capacity of existing runways must be increased, as shown in figure 21. At the same time, noise-abatement procedures, including steep two-segment approaches, will be required. These capabilities must be fully available in essentially all-weather conditions. Studies have shown that, to meet these requirements, the airplane must perform a combination of steep descent, rapid deceleration, and high-speed turnoff in low-visibility, windy weather. If systems can be developed to meet this combination of requirements, airport capacity can be appreciably increased, minimizing the need for more airport construction or service curtailment.

#### 4.1.5.2 State of Readiness

Some experience has been gained individually in two-segment approaches in good weather, low-visibility landings, high-speed turnoffs in good weather, and automatic braking. The combination of these in one sequence will require an unknown advance in information sensing, computation, monitoring, controls, and displays.

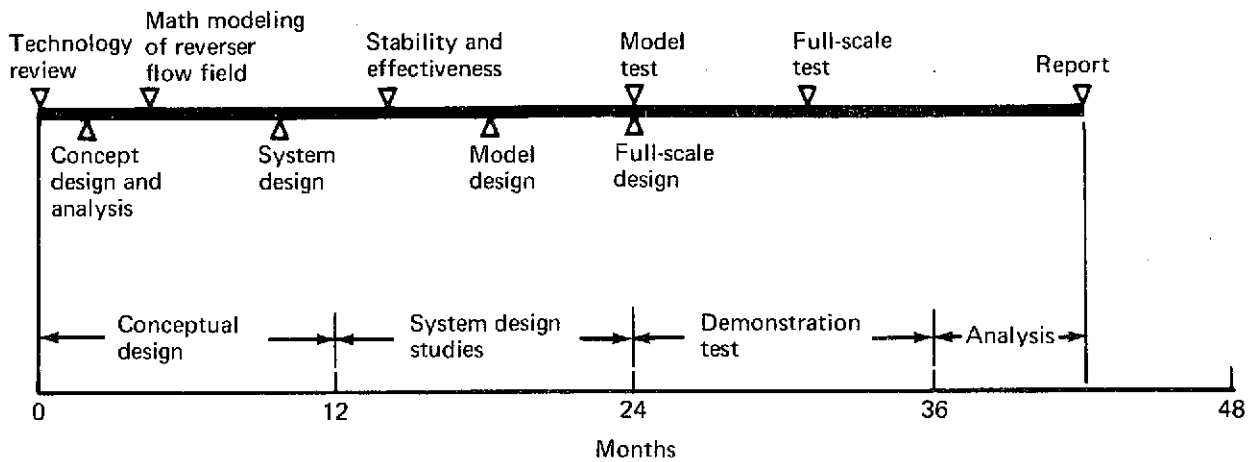
### WORK STATEMENT

- Review technology
- Design and analyze concept
- Math model reverser and flow field
- Model wind tunnel tests
- Flight test full-scale on 737

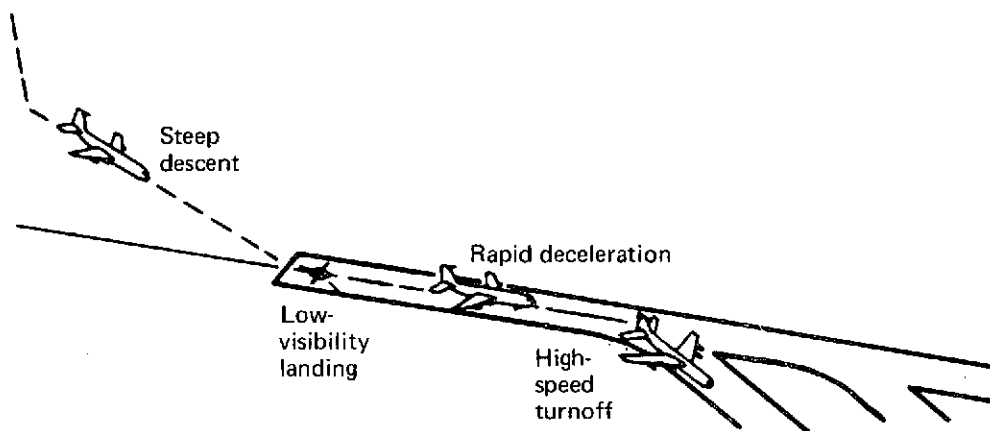
### PAYOFF

- Noise-abatement through steep descent
- Reduced engine spool-up time

### SCHEDULE



**FIGURE 20.—IN-FLIGHT THRUST REVERSERS**  
RESEARCH AND TECHNOLOGY SUMMARY



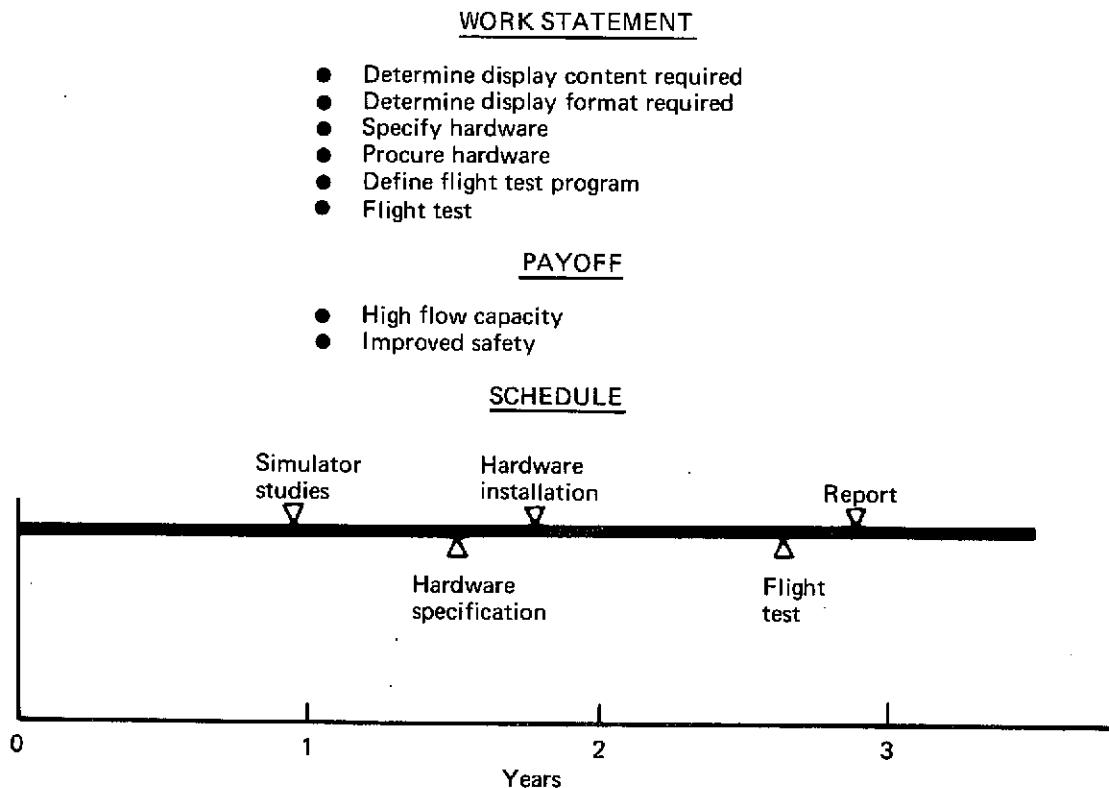
**FIGURE 21.—HIGH-FLOW-RATE LANDING SEQUENCE**

#### 4.1.5.3 Recommended Action

A simulation study of information and display requirements, followed by flight test of selected components and procedures, is recommended. A fixed-base visual simulator and a research airplane such as the NASA RSFS would be used to determine pilot performance and reaction with various levels of information content and accuracy and method of display for the combined approach, landing, and turnoff. These results would be verified by flight test of hardware developed to meet the requirements defined during the simulator study.

#### 4.1.5.4 Cost and Schedule

The scheduled program (fig. 22) would be of 2-1/2 years duration and cost \$700,000.



**FIGURE 22.—LANDING GUIDANCE  
RESEARCH AND TECHNOLOGY SUMMARY**

## 4.1.6 Work Package 6—Improved Anti-Icing Techniques

### 4.1.6.1 Potential Payoff

Development of anti-icing techniques that do not require excessive engine bleed or advanced engine power, figure 23, have several payoffs. These include: the lowest possible main engine thrust setting can be used during steep descents for noise abatement, thus minimizing source noise; smaller drag brake can be used; higher thrust is available on takeoff; or lower engine power setting could be used.

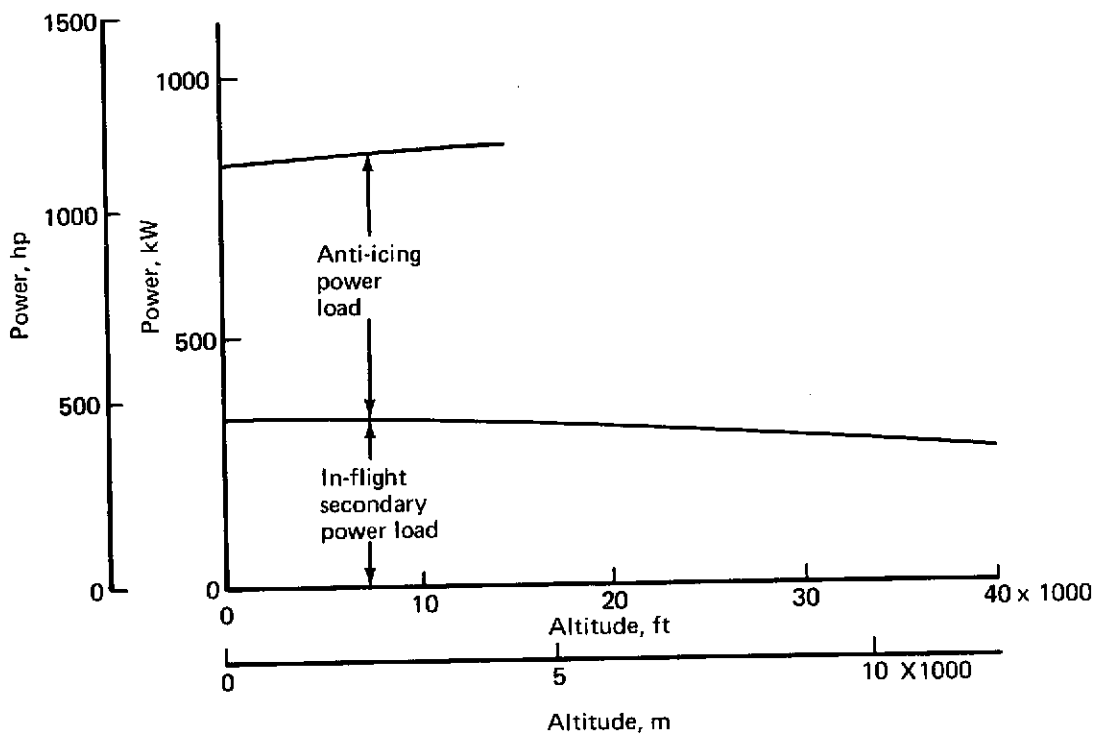


FIGURE 23.—ANTI-ICING POWER COMPARISON

### 4.1.6.2 State of Readiness

The primary technique used to provide engine inlet and airplane surface ice protection consists of supplying the required heat from main engine bleed air. Advanced engine power is normally required during holding and approach in icing conditions to ensure an adequate heat supply from the engines. On slower propeller-driven aircraft, mechanical ice shedding (pneumatic boots) has been used to provide the required protection.

A means of providing anti-icing for engine inlet and associated noise-reduction systems, as well as critical airplane surfaces, is required. This heat supply must be independent of airplane engine power setting. Studies have shown that the use of an in-flight APU as the heating air source would result in a considerable weight and cost penalty.

#### 4.1.6.3 Recommended Action

A two-phase program is recommended. The first phase would require a 1-year effort and cost \$100,000. It would consist of a review of airplane surface anti-icing requirements and the analysis of several alternate means of providing heat to the surfaces requiring protection, such as utilization of engine exhaust heat. The intent would be to identify those systems offering the most promise. The economics of each candidate system should be considered as well as the technological risk. Phase II would require 2 years and cost \$400,000. It would consist of the development of the best candidate system and subsequent flight test demonstration on a suitable aircraft, such as the RSFS.

#### 4.1.6.4 Cost and Schedule

The program schedule shown on figure 24 would cost \$500,000 and required 3 years to complete.

### 4.1.7 Work Package 7—Impact of Turbulence and Wind Shear on Airplane Design

#### 4.1.7.1 Potential Payoff

Wind shear and turbulence are important considerations in the landing of commercial jet airplanes. As an aircraft descends on an earth-referenced glideslope, a sudden change in the horizontal wind will instantaneously affect the velocity of the airplane with respect to the airmass. If the shear is such that the relative velocity of the airplane increases, the lift force will increase and the airplane will rise above the glideslope. If the engine thrust has been reduced to a minimum flight idle setting, as during a high glideslope noise-abatement approach, no further deceleration capability is available as a possible go-around situation develops. If a shear causes a sudden decrease in the relative velocity, the aircraft will respond by falling below the glideslope and a potentially dangerous condition could result.

The ability to maintain a constant airspeed while tracking a steep landing profile in a shearing tailwind will impose new requirements on the flight control system. In addition, the combination of wind shears and turbulence create stability, control, and flightpath position/prediction problems while impacting pilot workload. One method of dealing with the wind/weather disturbance has been with automatic controls and autopilot systems. This has been demonstrated by the use of inertial

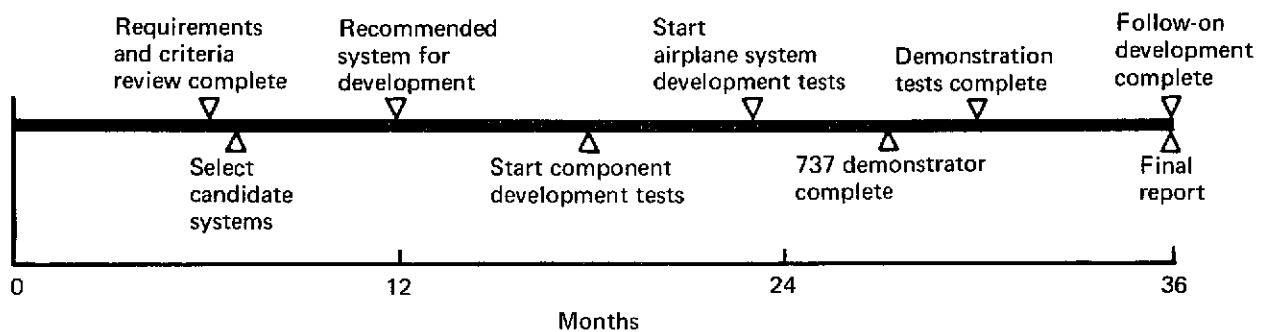
### WORK STATEMENT

- Phase I
  - Develop anti-icing requirements and review criteria
  - Analyze candidate anti-icing systems
  - Recommend systems for development
- Phase II
  - Development of candidate system
  - Flight test evaluation

### PAYOFF

- Reduced approach noise
- Smaller drag devices
- Higher takeoff thrust on icing days

### SCHEDULE



**FIGURE 24.—IMPROVED ANTI-ICING TECHNIQUES**

### RESEARCH AND TECHNOLOGY SUMMARY

smoothing. Incorporating drag brakes and automatic control systems to reduce airplane dependence on weather disturbances will reduce the number of aborted landings while providing an extra degree of safety. The minimization of future congestion will require airplanes with the ability to follow more complicated landing profiles precisely in the presence of wind shears and turbulence. To incorporate the necessary flight control system design items requires a better understanding of these low-altitude weather effects encountered during the landing approach maneuver.

#### 4.1.7.2 State of Readiness

The problem of quantitatively defining the effect of shear and turbulence has not been completely resolved. Various wind shear and turbulence studies have addressed the problems of what wind shear profile shapes are most critical during landing, which type of airplanes are most responsive to shear, and what meteorological parameters relate to the wind shears. However, an adequate wind shear and turbulence model has not been developed to date to which the flight control system can be designed. One method of dealing with the weather disturbance problem has



been demonstrated with the inertial smoothing automatic control system described in FAA-RD-72-22. This system demonstrated the ability of a Boeing 727 airplane to perform automatic landings in the presence of ILS beam anomalies.

#### **4.1.7.3 Recommended Action**

A four-phase program is recommended that leads to in-service evaluation of an automatic flight control system capable of handling expected wind shears and turbulence during the landing maneuver.

The initial phase would pull together all previous and current work directed toward developing a model for low-level wind shear and turbulence. New data from research aircraft such as the NASA RSFS would be included. From this collection, a design wind and turbulence model would be chosen to which an adequate flight control system could be designed.

Phase II would specify the flight control system elements required to implement noise-abatement landing approaches in the wind-shear/turbulence model. Candidate design items would include aerodynamic drag brakes, in-flight thrust reversing, low-cost inertial sensors, and automatic control system.

Phase III would integrate the required elements in the airplane design and research the feasibility on the simulator.

Phase IV would flight test the best candidate system for multisegment, decelerating, steep and curved approaches in high shear, and turbulent wind conditions.

#### **4.1.7.4 Cost and Schedule**

The 1-1/4-year program plan shown on figure 25 is estimated to require a total funding of \$1.5 million.

### **4.1.8 Work Package 8—Noise-Abatement Approach and Landing Study**

#### **4.1.8.1 Potential Payoff**

To reduce noise near airports, many studies and tests have been conducted on various approach profiles. Flight tests on a Boeing 367-80 have achieved a noise reduction of about 17 PNdB at a point 3.7 km (2 nmi) from the runway threshold on a single-segment approach by increasing the glideslope from 2.67° to 6°. For a two-segment approach with a 6° upper segment, a

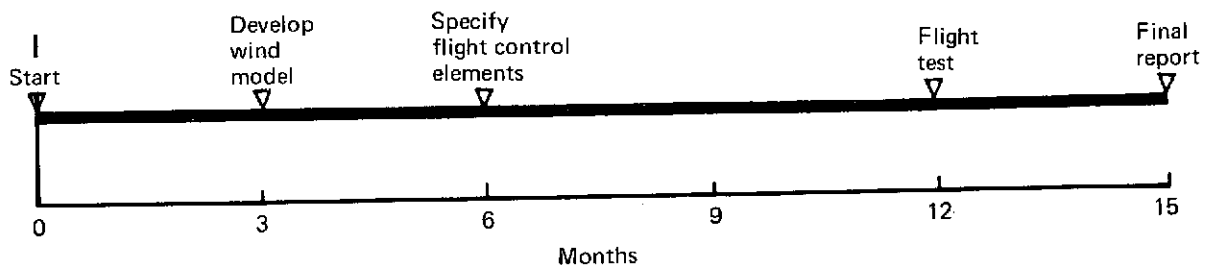
#### WORK STATEMENT

- Choose wind and turbulence model
- Specify flight control elements
- Integrate elements into aircraft design
- Simulator test to check feasibility
- Flight test to demonstrate capability

#### PAYOFF

- Capability to make noise-abatement landing approaches in wind shear and turbulence
- Reduced noise in landing approaches

#### SCHEDULE



**FIGURE 25.—IMPACT OF TURBULENCE AND WIND SHEAR ON AIRPLANE DESIGN**  
RESEARCH AND TECHNOLOGY SUMMARY

noise reduction of 11 PNdB at 2.0 km (1.1 nmi) was achieved. For a 122-m (400-ft) intercept altitude, there was no reduction at 1.85 km (1 nmi) and 10 PNdB at 2.8 km (1.5 nmi) and beyond. A decelerated approach with a  $5.4^\circ$  glideslope is shown with the TAC airplane in figure 26 on a two-segment approach with a  $5^\circ$  upper segment resulted in noise reductions as high as 11 PNdB at 2.0 km (1.1 nmi) from the runway threshold. Recent NASA studies have demonstrated two-segment approaches in a present-day commercial aviation environment. A new study program is proposed that would expand on these tests and establish operational parameters for a standard noise-abatement approach.

The objectives of the program would be to:

- a) Review past tests to determine best possible approach profile from noise-reduction standpoint.
- b) Make recommendations for other trajectories not previously tested, such as continuously curved path.

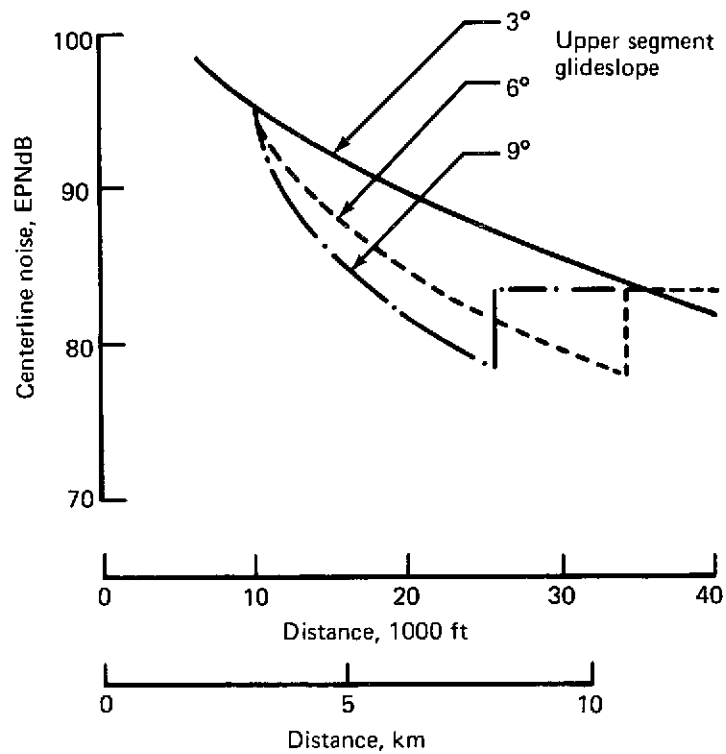
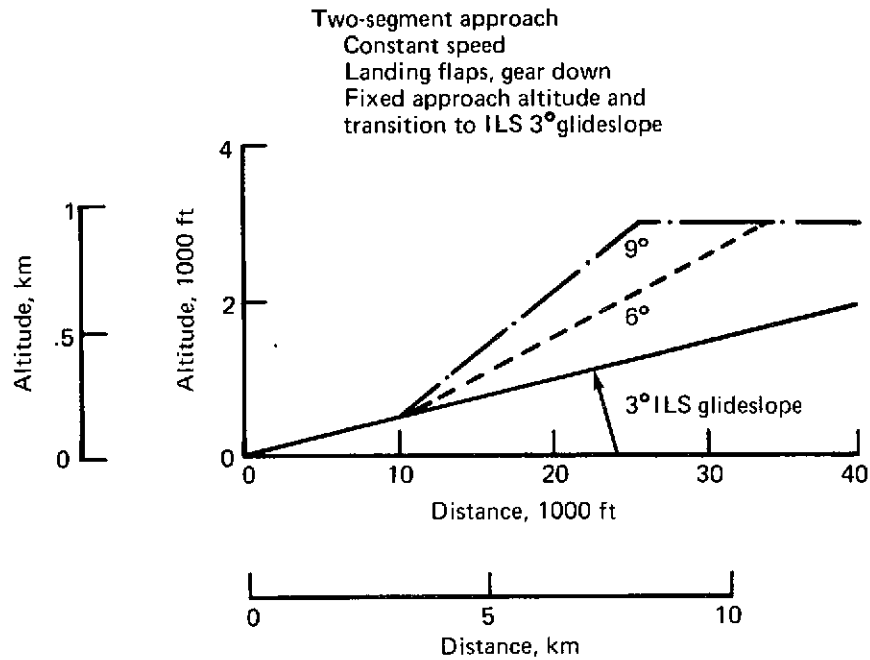


FIGURE 26.—NOISE-ABATEMENT-LANDING NOISE REDUCTION

- c) Determine solutions to problems associated with best trajectory. For example, the single-segment steep approach gave better noise reduction than the two-segment approach, but pilots were reluctant to hold high sink rates close to the ground. Equipment and procedure modifications to provide this approach without jeopardizing safety should be studied.
- d) Determine guidance requirements for flightpath accuracy. Large errors require large controls and thrust inputs resulting in greater pilot workload and noise.
- e) Evaluate safety of best approach profile.
- f) Determine requirements in aircraft capability to rapidly correct large deviations from the glideslope.
- g) Determine requirements to meet category III A, B, and C criteria.

#### 4.1.8.2 State of Readiness

The basic technical knowledge to complete this study exists. Previous test programs have shown the techniques, required guidance, and aircraft capabilities. These tests, however, were limited to  $6^\circ$  single-segment glideslope or  $6^\circ/2.65^\circ$  two-segment glideslope with intercept altitudes of 76 m (250 ft) and 122 m (400 ft). The 76-m (250-ft) altitude was unacceptable to the pilots, and no effort was made to find ways to make it acceptable.

#### 4.1.8.3 Recommended Action

It is recommended that a simulator and flight test program be initiated. The Boeing 737 has good capability in terms of steep glideslope without auxiliary devices; it is recommended that the RSFS be used for this study.

The study would be conducted in four phases:

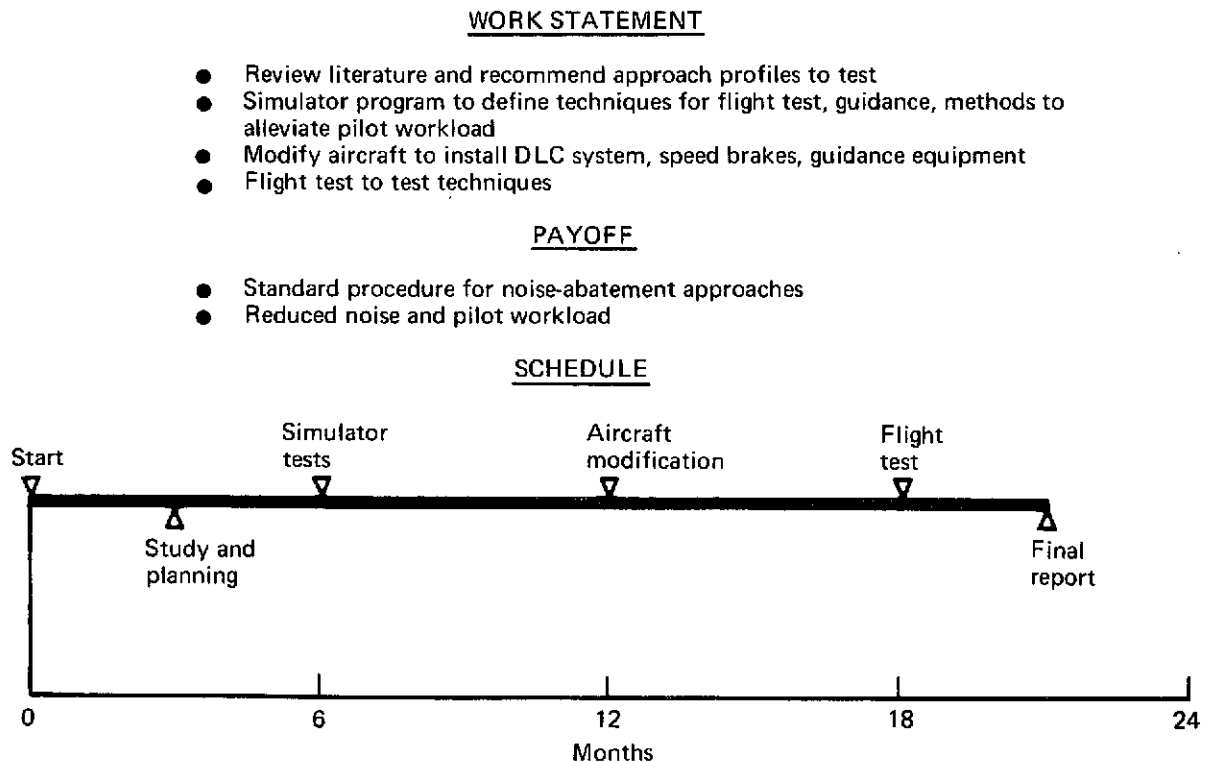
- a) Phase I—Review of literature on previous tests and recommendations for simulator and flight test programs: A study would be made of possible techniques and the most promising ones recommended.
- b) Phase II—Simulator programs to define possible techniques for flight test, guidance requirements, and methods of alleviating pilot workload: This phase should define operational parameters such as glidepath angle transition altitude and flare technique. It

should also determine any required configuration changes to meet objectives such as direct lift control (DLC) and side force control. Examine new pilot techniques with a view to making a lower transition altitude acceptable. Turbulence and wind shear could also be included, but this is the subject of another study.

- c) Phase III—Aircraft modification to incorporate DLC system, speed brakes, and guidance equipment.
- d) Phase IV—Flight test program to test the promising techniques: Emphasis would be on reducing pilot workload, improving safety, and making noise measurements. This program should develop standard operational procedures for noise-abatement approaches.

#### 4.1.8.4 Cost and Schedule

The 1-3/4-year program plan shown in figure 27 is estimated to require a total funding of \$3 million.



**FIGURE 27.—NOISE-ABATEMENT APPROACH AND LANDING STUDY  
RESEARCH AND TECHNOLOGY SUMMARY**

#### **4.1.9 Work Package 9—Stopping System Trades**

##### **4.1.9.1 Potential Payoff**

A key factor in the flow capacity at a runway is the rapidity with which the airplane can be slowed to turnoff speed after touchdown, figure 28. The passengers set the upper limit on deceleration level, but this level is high enough to exact penalties in weight or life of conventional brakes if they provide the primary braking force. Savings in brake weight, brake maintenance, and landing gear weight may be realized by alternative stopping devices.

##### **4.1.9.2 State of Readiness**

Thrust reversing devices are installed on most airplane engines. Their certification as part of the stopping system would probably require modest changes in reliability, redundancy, and control. Brake weight/energy/life trades are fairly well understood. The cost and reliability of reversing fans (which would have other benefits) is not well known.

##### **4.1.9.3 Recommended Action**

Sufficient data should be assembled to permit the preliminary design of alternative stopping systems using brakes, external thrust reversers, and reversible fans. The weight, cost, maintenance cost, and other pertinent factors would be estimated. Further research and hardware development would then be recommended based on the results of this comparison.

##### **4.1.9.4 Cost and Schedule**

The scheduled program (fig. 29), exclusive of later hardware development, would be of 1-year duration and cost \$200,000.

#### **4.1.10 Work Package 10—Noise Treatment Versus Noise-Abatement Procedures**

##### **4.1.10.1 Potential Payoff**

A trade study evaluating the relative merits of extensive engine nacelle treatment and steep approach could identify the safest, most economical method for reducing landing noise.

As shown in figure 30, the benefit of steep approach capability is that (1) it could reduce the 90-EPNdB landing contour of a peripherally treated engine to that of an extensively treated (two rings/one splitter) engine, (2) it could eliminate the cruise penalty associated with extensive

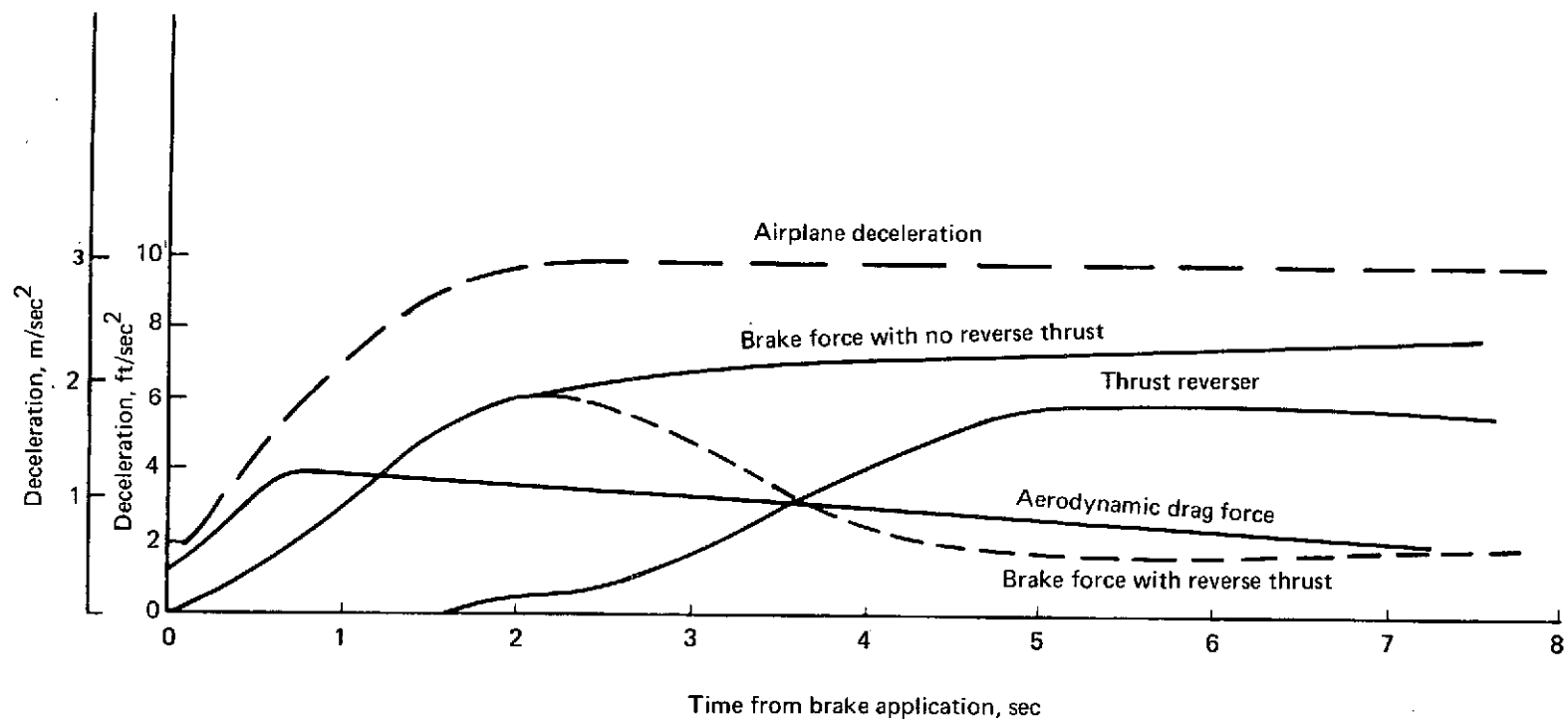


FIGURE 28.—ALTERNATIVE STOPPING FORCES

- Develop requirements
- Survey technology
- Configure alternative systems
- Evaluate alternatives

- Higher traffic flow rates
- Reduced weight penalty

A horizontal timeline diagram with a black bar representing the duration. The x-axis is labeled 'Months' with tick marks at 0, 6, and 12. Three milestones are marked with downward-pointing triangles: 'Requirements' at approximately month 2, 'Configurations' at approximately month 8, and 'Evaluation' at month 12.

acoustical treatment (two rings in inlet, one splitter in fan duct), (3) it would rule out structural failure of the inlet rings as a problem, and (4) it would provide operational flexibility.

The benefit of using extensive engine treatment is to (1) provide quiet approach with 3° landings and thereby alleviate the need for two-segment or steep landings, (2) reduce approach noise during low-altitude bad-weather approaches, and (3) reduce area enclosed by 95 to 100 EPNdB substantially more than the peripherally treated engine, although contours less than 90 EPNdB are nearly equal for the two treatments.

Preliminary investigations have been conducted to establish probable benefits of two-segment landings with several levels of engine treatment. These investigations indicated the payoffs described above, based on engine noise reductions. In addition, flight tests have been conducted with several JT8D quiet nacelles under several two-segment landings. However, the study omitted effects of airframe noise, and the flight test was conducted for a bypass ratio 1 engine. (The aircraft of 1985 are expected to use a bypass ratio 4+ engine.) Consequently, a more detailed investigation to include safety, equipment maintenance, pilot and airline preference, profitability, impact on congestion, and noise benefits is needed to determine recommended tests.



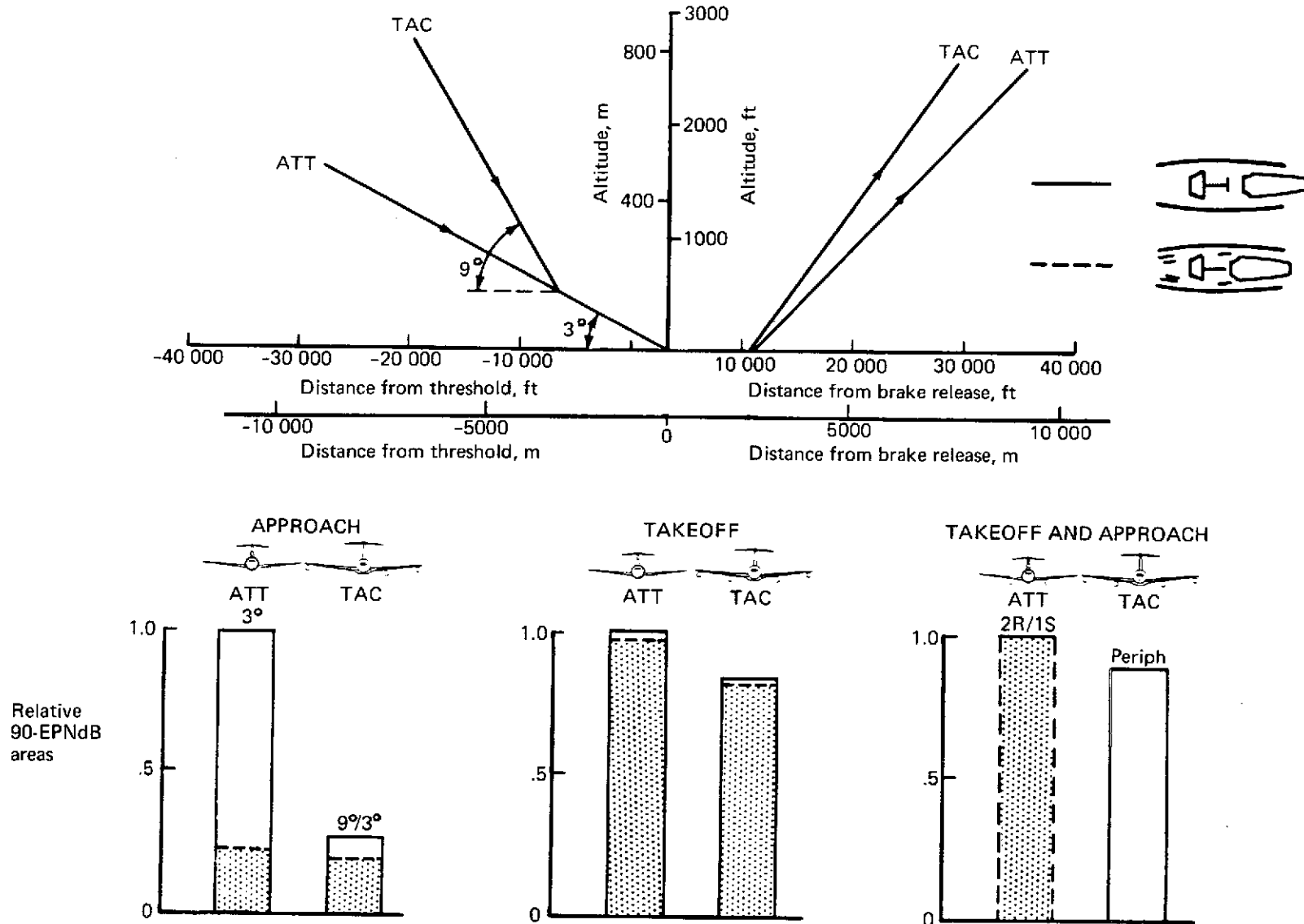


FIGURE 30.—NOISE TREATMENT VS STEEP APPROACH NOISE TRADES

#### 4.1.10.3 Recommended Action

A program involving all the related technical disciplines necessary to make a good evaluation of the landing alternatives is recommended. A number of combinations of engine treatments and steep approaches would be defined, and each would be evaluated in terms of safety, flight control, maintenance, economics, performance, and noise contour. Preferred alternatives would be recommended.

#### 4.1.10.4 Cost and Schedule

This 8-month study program (fig. 31) is estimated to cost \$350,000.

##### WORK STATEMENT

- Identify characteristics of extensive noise treatment so economics, maintenance, safety, noise control, etc., analysis can be made
- Identify important aspects that affect noise-abatement landings
- Determine effects of extensive noise treatment and noise-abatement landings on economics, safety, maintenance, etc.

##### PAYOFF

- Develop the most sound method for reducing landing noise: theoretical basis
- Identify R&D items holding up implementation

##### SCHEDULE

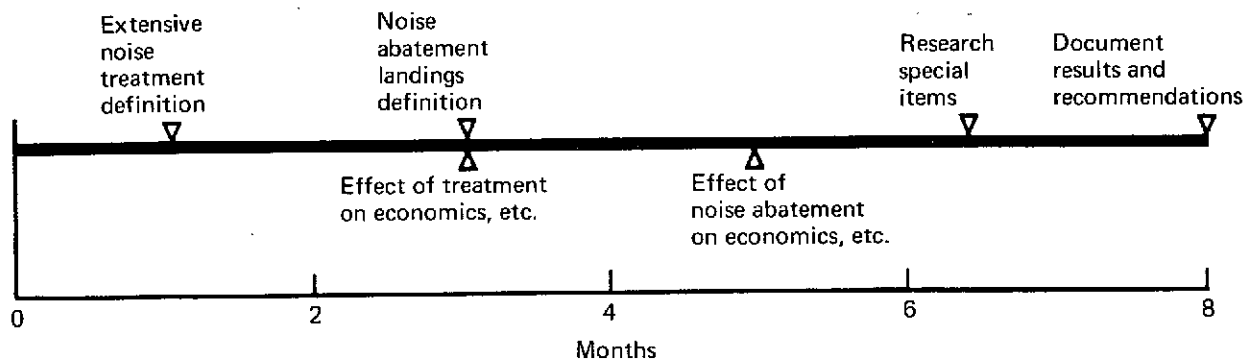


FIGURE 31.—NOISE TREATMENT VS NOISE-ABATEMENT PROCEDURES  
RESEARCH AND TECHNOLOGY SUMMARY

#### **4.1.11 Work Package 11—Engine Component Noise Research**

##### **4.1.11.1 Potential Payoff**

A program to further identify the frequency content and angular distribution of jet noise, core noise, fan noise, and inlet noise would result in three major advantages:

- a) Increased noise prediction accuracy, which leads to a more optimized aircraft
- b) Better opportunity for suppressing the noise source or component
- c) More cost-effective apportionment of treatment

##### **4.1.11.2 State of Readiness**

Noise source isolation tests have been conducted by Boeing in conjunction with the JT3D, JT8D, and JT9D engines. General Electric has done extensive investigations of the CF6-6D. Together, there has been a great amount of data collected on engines of different bypass ratios, pressure ratios, turbine temperatures, and fan stages. What is needed now is a program to tie together the data that collected from the various investigations to arrive at a noise-prediction program that can more accurately predict the noise characteristics of the various engine components over a wide bypass ratio range. Special attention would be given to fan and inlet noise analysis since these noise components are expected to dominate the 1985 terminal-compatible engine.

##### **4.1.11.3 Recommended Action**

The program would include the following:

- a) Analyze JT9D, CF6-6D, and CF6-50D engine noise data to evaluate effects of bypass ratio 4 to 6, one-stage fans.
- b) Compare JT8D-15 two-stage fan noise with JT8D refan one-stage fan noise. Compare JT3D-3B two-stage fan noise with JT3D refan program research results.
- c) Correlate engine fan pressure ratio effect, blade number effect, fan tip velocity effect, rotor-stator spacing effect, etc., on discrete and broadband noise.
- d) Determine effects of turbine pressure ratio, combustor exit temperature, combustor mass flow, etc., on core noise.

- e) Determine effect of relative velocity on jet noise.
- f) Develop a noise-prediction method that will accurately describe the noise for an engine between bypass ratios 4 and 6, applicable to a terminal-compatible aircraft in 1985.

#### 4.1.11.4 Cost and Schedule

This 9-month program (fig. 32) is estimated to cost \$500,000.

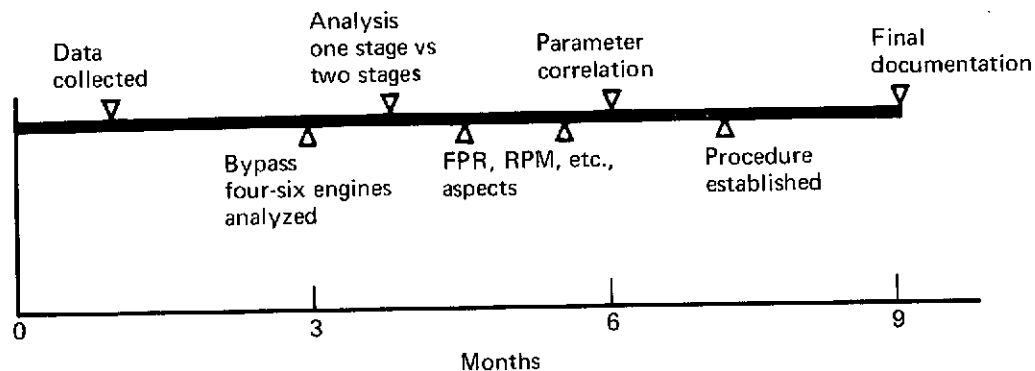
##### WORK STATEMENT

- Collect data on JT9D, CF6-6D, CF6-50D, and other high-bypass engines, both one- and two-stage fans
- Correlate data with engine parameters
- Develop a noise-prediction method accurate for post-1985 terminal-compatible aircraft

##### PAYOFF

- Increased noise prediction accuracy
- Better opportunity to quiet source of noise

##### SCHEDULE



**FIGURE 32.—ENGINE COMPONENT NOISE RESEARCH**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.1.12 Work Package 12—Engine Noise Reduction With Lining/Treatment

##### 4.1.12.1 Potential Payoff

Engine noise reduction by acoustic treatment can provide 10 to 12 EPNdB noise reduction for bypass ratio four engines during both takeoff and landing. This reduction is accomplished by suppressing the inlet and fan noise. The suppression benefit is achieved over an altitude range from 61 to 305 m (200 to 1000 ft) and decreases to about 0.5 EPNdB at 914 m (3000 ft) altitude. At

914 m (3000 ft) altitude, the aircraft noise is relatively quiet and is dominated by low-frequency noise. Consequently, the high-frequency fan and inlet treatments provide little suppression when the aircraft is at 914 m (3000 ft) altitude.

#### 4.1.12.2 State of Readiness

Acoustical inlet and fan duct treatments have been developed for the JT9D, JT8D refan, and CF6-6D. Sonic engine inlets have been designed and tested for their ability to attenuate inlet noise. What is needed now is an effort to suppress an engine closely resembling the bypass ratio 4 ATSA-4-2800-24 engine.

#### 4.1.12.3 Recommended Action

The following program is recommended:

- a) Use results of the engine component noise research program to define engine characteristics of the bypass ratio four engine.
- b) Select an engine most representative of the bypass ratio four ATSA-2800-24 engine.
- c) Install that engine on a NASA research aircraft.
- d) Peripherally treat inlet and fan duct with various materials.
- e) Flight test two-segment and 3° approaches and normal takeoff to evaluate 90-EPNdB contours and FAR Part 36 noise.
- f) Add rings and splitter to engine configuration.
- g) Flight test two-segment and 3° approaches and normal takeoff with added rings and splitters to evaluate 90-EPNdB contours and FAR Part 36 noise.

#### 4.1.12.4 Cost and Schedule

This 2-year program (fig. 33) is estimated to cost \$3 million.

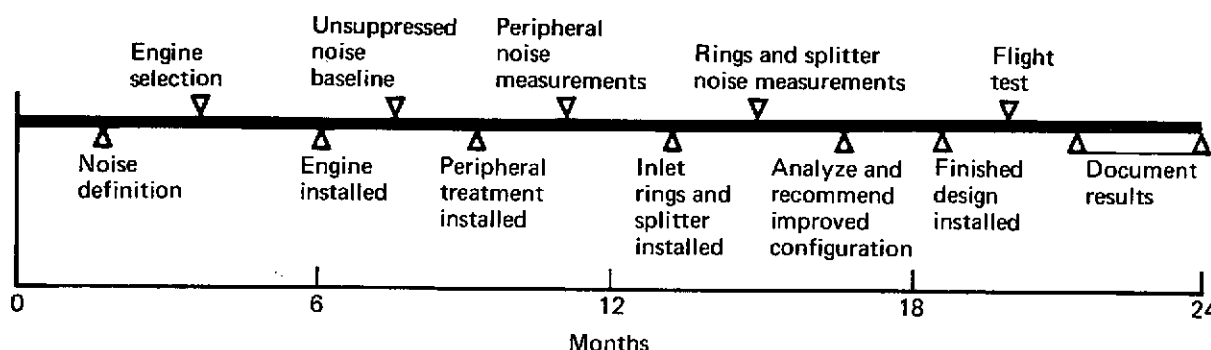
### WORK STATEMENT

- Define engine noise
- Select representative engine and install on research aircraft
- Peripherally treat engine and flight test (3° vs noise abatement)
- Add rings and splitter and flight test (3° vs noise abatement)
- Make noise measurements during flight test
- Analyze noise and make recommendations

### PAYOFF

- 10- to 12-EPNdB reduction in landing noise relative to unsuppressed, unabated landing

### SCHEDULE



**FIGURE 33.—ENGINE NOISE REDUCTION WITH LINING/TREATMENT  
RESEARCH AND TECHNOLOGY SUMMARY**

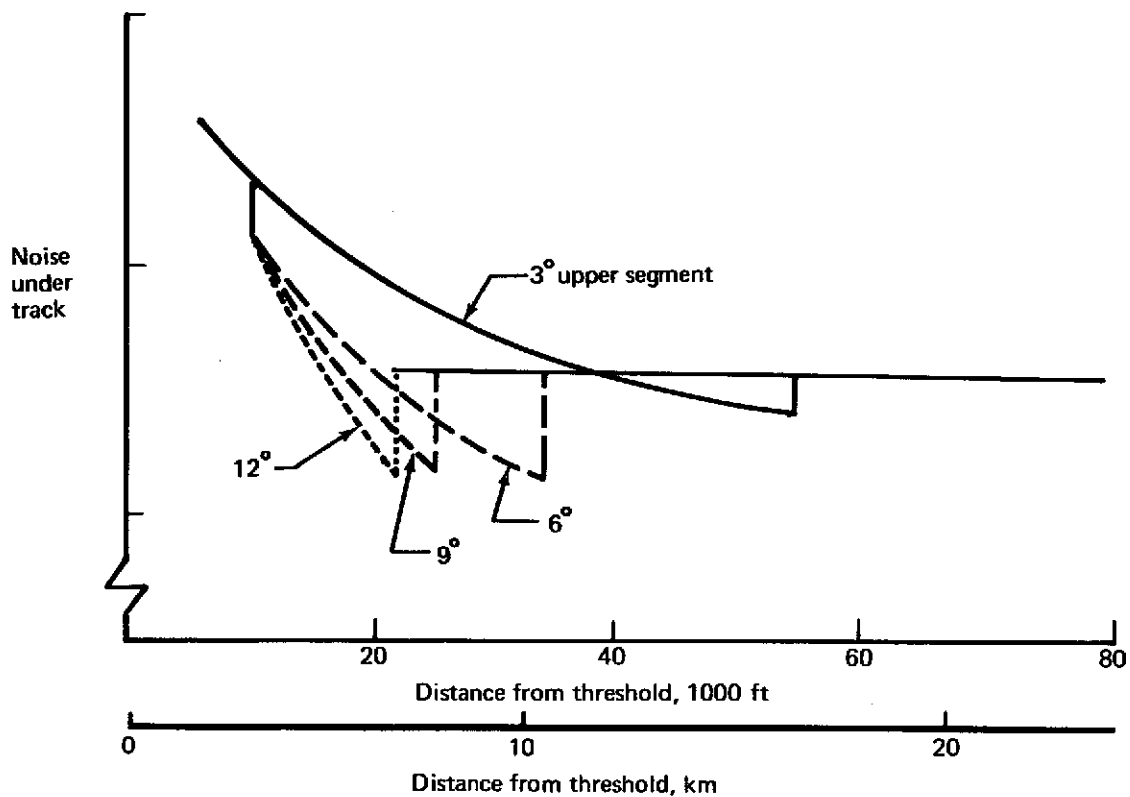
#### **4.1.13 Work Package 13—Steep-Approach Operational Compatibility**

##### **4.1.13.1 Potential Payoff**

Steep, two-segment approaches considerably reduce the noise level along the approach corridor, figure 34, especially when the first intercept altitude is high. This reduction in noise at the ground for a given aircraft source noise level can be used in conjunction with engine and nacelle modifications to reduce the affected community area. These procedures may be an alternative to the cost, weight, and reduced efficiency of extreme source-noise reduction measures.

##### **4.1.13.2 State of Readiness**

Moderately steep, two-segment approaches are currently being demonstrated in limited operational areas. The airplane technology to perform steep approaches safely is the subject of other research items. However, the operational problems of widespread, but not universal, use of steep approaches have not been studied in depth. Areas requiring resolution include the ATC interface in terms of airspace, navigation aids, surveillance and control procedures, pilot training,



**FIGURE 34.—NOISE REDUCTION WITH STEEP APPROACHES**

and passenger acceptance. Mixed steep and conventional approaches in the same airspace introduces problems that do not lend themselves to simple solutions.

#### 4.1.13.3 Recommended Action

An analytical evaluation of ATC interface problems at representative airports is recommended. This activity would be coordinated with simulator and flight test evaluation of steep approach hardware for pilot and passenger factors.

Five to 10 specific airports, covering a wide range of traffic patterns and noise-sensitive areas, would be chosen for analysis. For each airport, three-dimensional approach and departure paths would be defined for mixed two-segment and conventional approaches. Control procedures for this mixed traffic would be developed.

In conjunction with steep two-segment approach simulation and flight test, pilots would be asked to intermix steep approaches with conventional approaches, and their performance and comments would be evaluated.

#### 4.1.13.4 Cost and Schedule

This program (fig. 35) would be of 1-year duration and cost \$200,000.

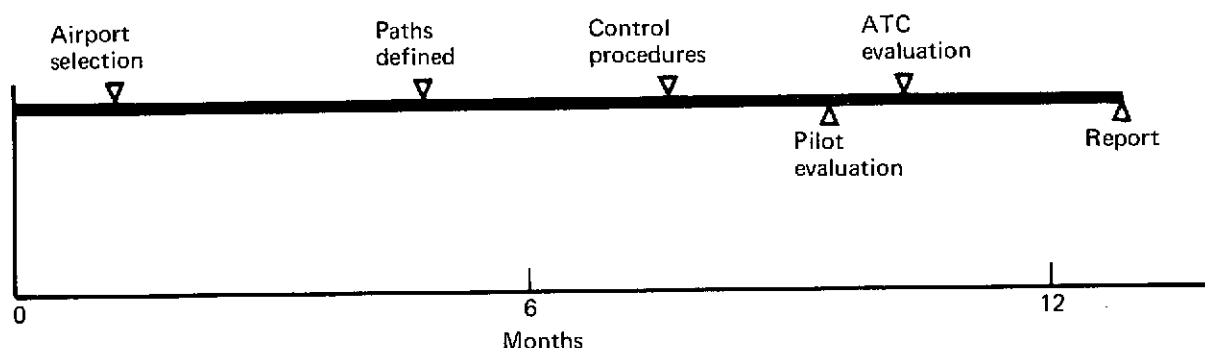
##### WORK STATEMENT

- Select airports
- Define approach and departure paths
- Develop mixed-traffic control procedures
- Evaluate conflicts
- Evaluate pilot performance

##### PAYOFF

- Lower community noise
- Less source noise reduction required

##### SCHEDULE



**FIGURE 35.—STEEP APPROACH OPERATIONAL CAPABILITY**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.1.14 Work Package 14—Passenger Compartment and Flight Deck Noise

##### 4.1.14.1 Potential Payoff

The purpose of this program is to understand the noise characteristics of the speed brakes, the wingtip drag device vortex inhibitor, and the advanced APU to permit design of a quiet aircraft interior during approach.

##### 4.1.14.2 State of Readiness

Speed brakes smaller in size but similar in design to those on the terminal-compatible aircraft have already been employed on aircraft. Drag chutes have been used with military aircraft. The APU in the RSFS could be used to simulate in-flight APU operation. Noise transmission characteristics of



the 737 and other Boeing aircraft are well defined. All of these facts lead us to believe that the technology is in hand well enough to conduct tests to determine the noise characteristics of the speed brakes, drag devices, and APU recommended for an aircraft compatible with 1985 requirements.

#### 4.1.14.3 Recommended Action

A program is recommended to:

- a) Design speed brakes, drag devices, and/or other vortex dissipators and APU modifications.
- b) Flight test each device separately, with variations in device parameters, taking interior noise measurements. Recommend any additional interior noise insulation required for quiet aircraft interior.

#### 4.1.14.4 Cost and Schedule

The 6- to 9-month program (fig. 36) would cost between \$0.5 to \$1 million.

### 4.1.15 Work Package 15—Post-1985 Noise Criteria

#### 4.1.15.1 Potential Payoff

A study to develop post-1985 noise criteria will be beneficial in defining environmentally permissible takeoff and approach noise contour shapes and contour levels. The study will also assist in defining a flexible aircraft—an aircraft that can be grown in size and still achieve the necessary noise levels. The study should lead to aircraft design requirements for noise that will provide the aircraft with a long and useful life within known performance and economic assessments.

#### 4.1.15.2 State of Readiness

Similar studies have been conducted for STOL aircraft utilizing STOL airports. In addition, airport suitability studies have been conducted for the SST. However, neither of these studies serves to define the post-1985 noise criteria. A new study is required to look at the noise restrictions of the many commercial airports.

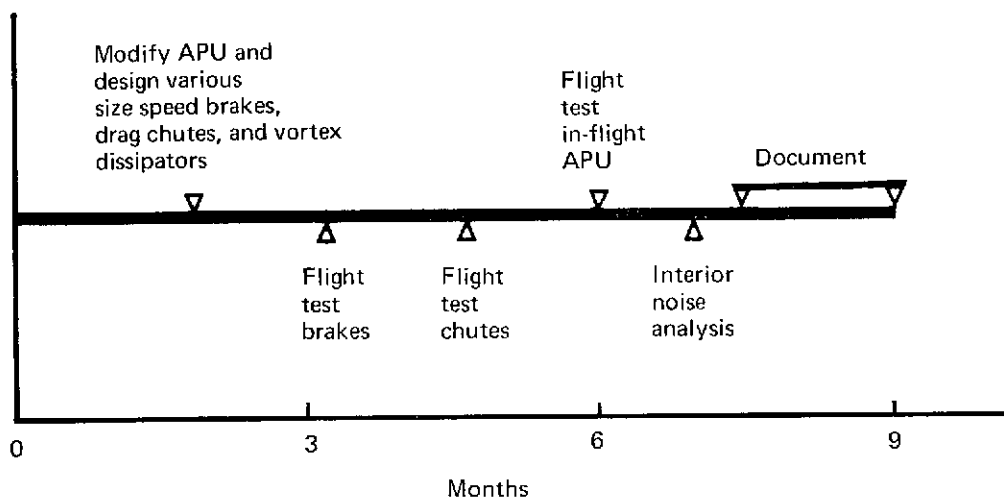
#### WORK STATEMENT

- Design speed brakes, drag chutes, APU modifications
- Individually flight test, taking interior noise measurements
- Recommend any additional interior noise insulation required for quiet aircraft interior

#### PAYOFF

- Quiet aircraft interior for post-1985 terminal-compatible aircraft

#### SCHEDULE



**FIGURE 36.—PASSENGER COMPARTMENT AND FLIGHT DECK NOISE**

#### RESEARCH AND TECHNOLOGY SUMMARY

##### 4.1.15.3 Recommended Action

A study program is recommended that would:

- Determine probable post-1985 community boundaries around selected representative airports, including probable airport expansion. A cross section of U.S. airports should be studied.
- Determine the number of 1985 airports that can be represented by selected airport dimensions.
- Determine the innermost airport boundary that would satisfy 60%, 70%, and 80% through 100% of airports boundaries.

- d) Determine aircraft noise contours during takeoff and landing.
- e) Compare these contours with airport/community interface points.
- f) Determine annoyance levels of terminal-compatible aircraft.
- g) Assess performance and economic trades versus noise.
- h) Considering airport size distribution, surrounding land-use economics, and airplane noise/cost relationships, recommend post-1985 noise goals.

#### 4.1.15.4 Cost and Schedule

This 8-month program (fig. 37) is estimated to require \$100,000.

## 4.2 RESEARCH AND DEVELOPMENT AFFECTING GROUND OPERATIONS

Ground operations are critical to flow capacity, to acceptance of arriving airplanes after they have landed, and to the pollution contributed to the airport vicinity by the airplanes. The research items in this section address these problems (see fig. 38).

### 4.2.1 Work Package 16—Engine Emission Control

#### 4.2.1.1 Potential Payoff

One method for improving air quality in the vicinity of an airport is to reduce aircraft engine emissions. The level of control technology effort, however, is presently tailored to meet the 1979 EPA emission standards.

To meet the more stringent emission requirements of the post-1980 TAC program would require advanced emission control research. It is desirable to know the cost of meeting these requirements so that rational decisions can be made as to the relative requirements imposed on airplanes and other sources of pollutants.

#### 4.2.1.2 State of Readiness

On July 17, 1973, the EPA released engine emission standards for aircraft. These standards

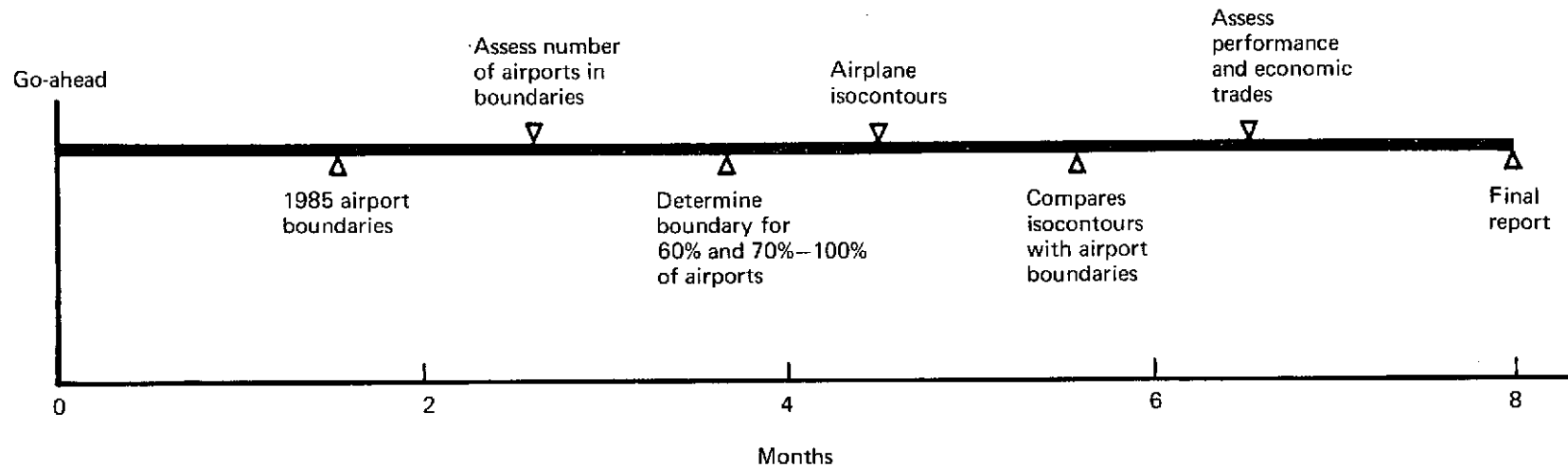
#### WORK STATEMENT

- Study physical dimensions of selected representative airports
- Determine isonoise contours of selected aircraft during takeoff and landing
- Compare contours with physical dimensions of airports
- Determine annoyance level of aircraft to the surrounding community
- Develop trades of performance and economics traded against annoyance of surrounding community

#### PAYOFF

- Definitive noise level design goals
- State-of-art calculations of airplane performance and economic penalties to achieve these goals

#### SCHEDULE



*FIGURE 37.—POST-1985 NOISE CRITERIA*

RESEARCH AND TECHNOLOGY SUMMARY

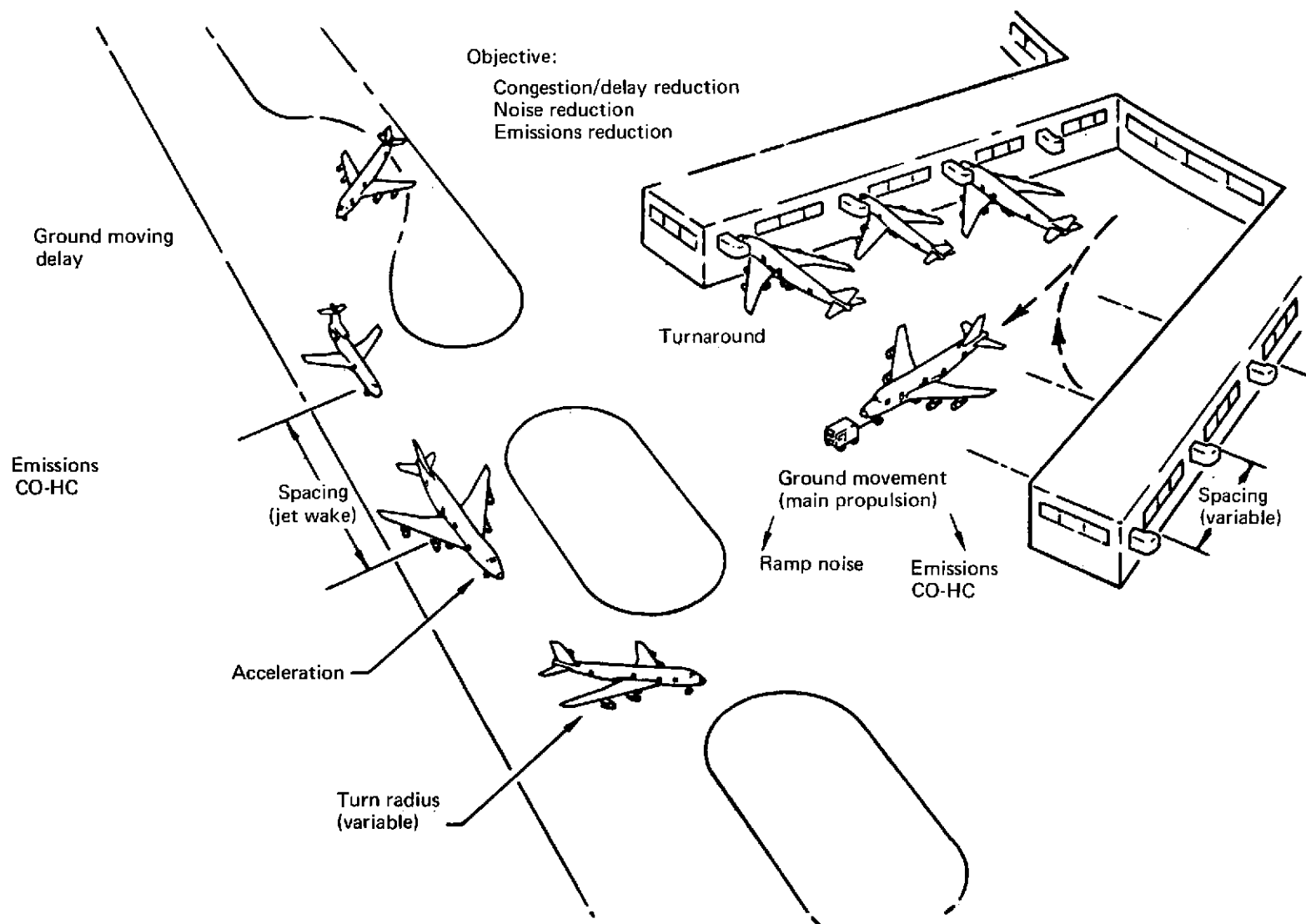


FIGURE 38.—RESEARCH AND TECHNOLOGY AFFECTING GROUND OPERATIONS

were based on emission control programs being conducted by the Air Force and NASA for combustor changes to promote better mixing and fuel vaporization.

Premix, fuel/air swirling, and dual-staging combustion are some of the concepts scheduled for testing in programs to meet 1979 EPA emission standards. More advanced combustor concepts applicable to goals for the 1985 TAC airplane are not being emphasized in this program, which is oriented toward developing and applying technology to meet the EPA 1979 emission standards. Today, there is doubt that the technology developed will be able to meet the 1969 NOX standard without the use of water injection. There is also serious doubt that the technology learned from these programs will be able to meet the 1981 EPA emission standards for HC and CO.

Combustor redesign for emission control is complicated by the fact that emission reduction must occur at both low and high power settings. Different pollutants behave entirely differently at different power settings. For example, NOX emissions are high at high power settings, but negligible at lower power. HC and CO are just the opposite. Combustors, therefore, cannot be redesigned just for takeoff or idle conditions, but must be designed for minimum emissions of all pollutants at all relevant power settings.

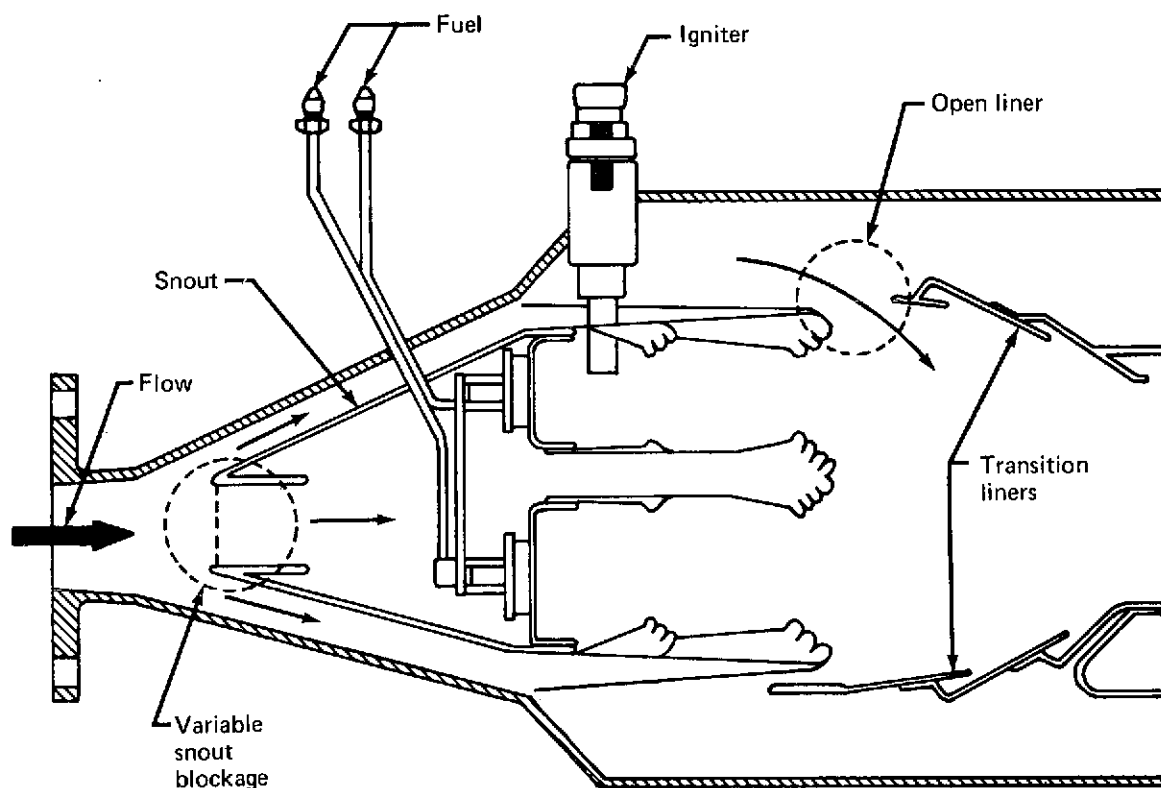
#### 4.2.1.3 Recommended Action

A major method of reducing emissions is to provide a more uniform local fuel/air ratio. Advanced prevaporization and premix developments are recommended to effect more uniform fuel/air ratios. To permit sustained combustion during idle, a dual fuel system could be used. This system involves the use of a volatile fuel during idle and a conventional fuel during cruise. Advanced additive injection techniques designed for pollution control should be explored. Possible injection points are the compressor, the combustor inlet, and the combustion chamber. The testing of different additives is also recommended.

Catalyst investigations are recommended to determine emission reduction through lower burn temperatures. Advanced variable-geometry systems (fig. 39) investigations are recommended for more precise fuel/air ratio control at low power settings. Analytical and limited test studies would be carried out on all concepts, followed by modification and test of an engine incorporating the most promising approaches.

#### 4.2.1.4 Cost and Schedule

Total cost of this program (fig. 40) is estimated at \$10 million.



**FIGURE 39.—VARIABLE-GEOMETRY ENGINE EMISSION CONTROL CONCEPT**

## 4.2.2 Work Package 17—Auxiliary Power Unit Development

### 4.2.2.1 Potential Payoff

The APUs on present airplanes have high maintenance costs that make them expensive for full-time in-flight use. Improvements in reliability, efficiency, and noise and emissions characteristics are essential for flexible secondary power system design.

Operating an in-flight APU could result in reductions in noise during approach and landing due to reductions in main engine power requirements and reduced ramp noise levels at the terminal. In addition, studies conducted for the AST airplane under NASA contract NAS1-10893 showed that integration of the APU with the secondary power system could result in a significant weight savings.

### 4.2.2.2 State of Readiness

The APU engine design considerations have been primarily the same as those applied to the main airplane engines. However, main engines normally run at relatively constant power settings and

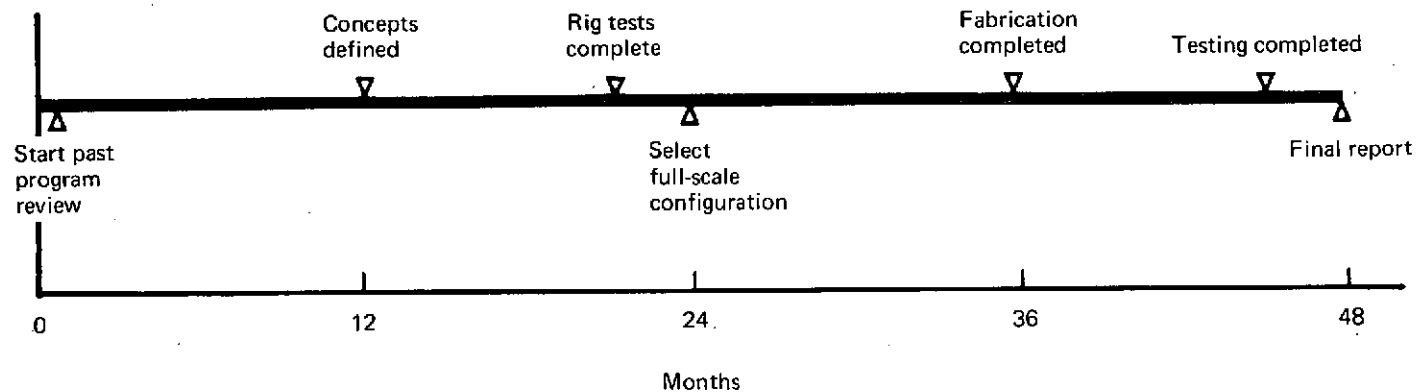
#### WORK STATEMENT

- Define concepts
- Rig test
- Select full-scale configuration
- Fabricate
- Test
- Recommend for manufacturer development

#### PAYOFF

- Develop required emission control technology for 1985 airplane system

#### SCHEDULE



*FIGURE 40.—ENGINE EMISSION CONTROL*

RESEARCH AND TECHNOLOGY SUMMARY



experience maximum power operation for relatively short time intervals. The APU is operated at essentially 100% power continuously with a requirement for nearly constant rotor speed. In addition, the control system must sense varying accessory power extraction requirements and adjust the output power distribution accordingly. Technology advances are required in the areas of control and engine and accessory component reliability, which could be applied to an integrated APU/accessory design.

#### 4.2.2.3 Recommended Action

It is recommended that studies be initiated to determine which elements of the APU and its control system cause a large degree of APU unreliability. Development work should then be conducted in the areas identified to establish requirements and potential solutions to the identified problem areas. The first phase would be a 6-month program with an estimated cost of \$100,000. It would include review of historical industry data, analysis, generation of design requirements, and preliminary definition of potential candidate improvement areas. Principles for increasing accessibility would be considered so as to minimize maintenance costs when failures do occur. The second phase would be a 2-year program with a cost of \$300,000 per year. It would include establishing a system configuration compatible with the requirements shown in figure 41, development and testing of key components, development of an APU system, and operational testing of appropriate hardware. Methods of reducing APU inlet and exhaust noise would also be conducted.

This program could be conducted in conjunction with the APU integration program recommended in response to NASA contract NAS1-10893.

#### 4.2.2.4 Cost and Schedule

The program plan is shown in figure 41 and will require 2-1/2 years with a total funding of \$700,000.

### 4.2.3 Work Package 18—Tire Technology

#### 4.2.3.1 Potential Payoff

Design modifications for reducing congestion and pollution involve larger brakes and powered wheels. These put greater demands on the available space within the wheels. Lower aspect ratio tires would provide this additional space without increasing the tire outside diameter (a stowage configuration problem) and weight.

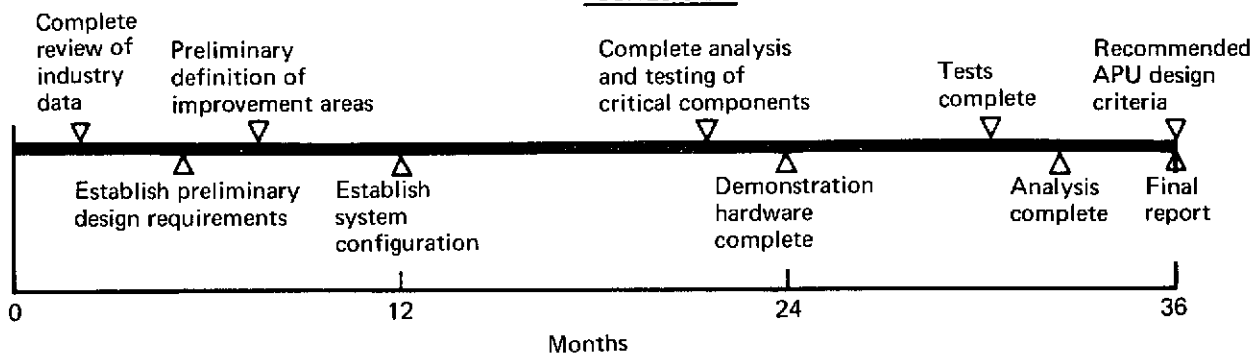
### WORK STATEMENT

- Phase I
  - Determine APU elements requiring improvement
  - Establish potential problem area solutions
  - Develop control and component criteria and requirements
- Phase II
  - Develop and test critical components
  - Establish test configuration
  - Operational test system

### PAYOFF

- Reduced maintenance costs
- Increased reliability
- Reduced noise
- Reduced emissions

### SCHEDULE



**FIGURE 41.—AUXILIARY POWER UNIT DEVELOPMENT**

### RESEARCH AND TECHNOLOGY SUMMARY

High deceleration stopping, which requires larger brakes, also puts a greater demand on the tire. This results in greater tire wear and more frequent tire failures, thus increasing maintenance costs. New materials and tire construction methods that reduce tire wear while providing good traction under all runway surface conditions are required to reduce tire maintenance costs and improve reliability.

One of the primary design parameters affecting the required torque for powered wheels is the amount of cold set in the tire. Materials that minimize this phenomenon would reduce the size and weight of the powered-wheel unit and improve the efficiency of the total airplane system.

#### 4.2.3.2 State of Readiness

Low-aspect-ratio tires are presently in limited use, and the major tire manufacturers are currently involved in studies of new concepts. However, most of these efforts are done on an

as-needed basis, the desired configuration is obtained but at the expense of tire carcass life, rolling resistance, or other operating characteristics.

Tire wear and traction have been the subject of study for over 50 years. Many experimental and analytical efforts have been undertaken. Unfortunately, there has been little effort put into translating the work at the microscopic level to the macroscopic level. Whereas the polymer scientists have generally used precise controls in evaluating materials, the rubber manufacturers have applied screening methods that sometimes fall short of realistic test methods. The problems seem to be improper control of variables, accelerated test conditions, and little or no rational approach to correlate the results obtained from full-scale tires.

New materials for tire carcass construction are being studied by the tire manufacturers, but these efforts should be coordinated with powered-wheel studies so that a tradeoff can be made between tire weight and powered-wheel requirements.

#### 4.2.3.3 Recommended Action

A multiphase development program that culminates in a service evaluation of a new tire design is recommended.

a) Phase I

- 1) Specify test conditions and equipment required for evaluation of tire tread stock for wear rate and traction.
- 2) Specify test conditions and equipment required for evaluation of tire carcass materials for strength and thermal properties.

b) Phase II—Develop test equipment and perform

- 1) Tread stock tests
- 2) Carcass materials tests

Select candidate materials for full-scale tire tests. Trade carcass material weight against powered-wheel system weight.

c) Phase III—Build full-scale tires and run qualification tests.

- d) Phase IV—Procure and install tires for flight tests on the RSFS. Sufficient testing would be accomplished to permit certification for airline use. Breakaway forces would be evaluated.
- e) Phase V—Procure and install hardware for one in-service airplane for airline evaluation. Tires would be evaluated through several recaps.

#### 4.2.3.4 Cost and Schedule

A 3-1/2-year program (fig. 42) with a total funding of \$500,000 is estimated.

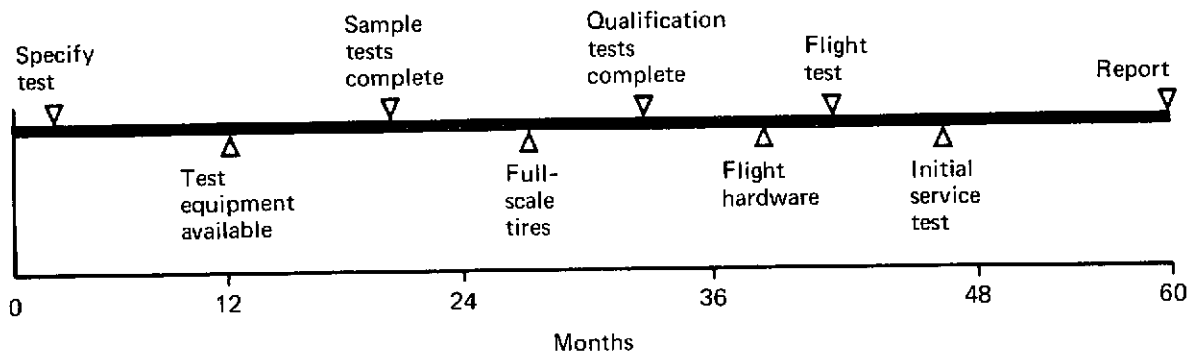
##### WORK STATEMENT

- Specify test conditions and equipment
- Develop test equipment and test
  - Tread stock
  - Carcass material
- Build full-scale tires and qualify on dynamometer
- Flight test evaluation and certification
- Service test

##### PAYOFF

- Reduced tire wear
- Improved traction
- Reduced powered-wheel torque required

##### SCHEDULE



**FIGURE 42.—TIRE TECHNOLOGY**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.4 Work Package 19—Landing Gear/Brake Dynamics

##### 4.2.4.1 Potential Payoff

The high deceleration rates required for early runway turnoff to reduce runway congestion require a smooth braking system. Passengers can tolerate higher deceleration forces only if the rate

of change of deceleration is low and the system is free of vibration. The brake control system cannot operate smoothly if subjected to severe brake vibration.

The fatigue life of many landing-gear-mounted components can be improved through the reduction of brake vibration.

#### 4.2.4.2 State of Readiness

Every jet transport aircraft in service to date has been subjected at one time or another to annoying brake-induced vibration, some to the extent that it has affected the operation of other systems. Many efforts have been undertaken to reduce brake-induced vibration in attempts to undo an intolerable situation after a brake has been qualified and, in some cases, in service.

Brake vibration is not understood to the extent that a brake can be designed for vibration-free performance. Much effort is required to study not only the contribution of the rubbing surface materials, but also the coupling effects of the hydraulic system and the basic structure.

#### 4.2.4.3 Recommended Action

A multiphase program is recommended.

- a) Phase I—Evaluate vibration characteristics of various lining/rubbing surface materials. A lining test facility would be required for sample tests.
- b) Phase II—Develop analytical methodology to predict impact of lining characteristics on brake dynamics, brake system, and the landing-gear system.
- c) Phase III—Develop a test procedure to evaluate the effects of the lining characteristics on brake primary structure and hydraulic actuation system design. Establish criteria for brake specifications based on the results of these tests and preceding analyses.
- d) Phase IV—Develop a brake system based on the established criteria through test and analysis.
- e) Phase V—Test the brake system under operational conditions and evaluate its vibration characteristics.

#### 4.2.4.4 Cost and Schedule

The five-phase program plan shown in figure 43 will cost \$700,000.

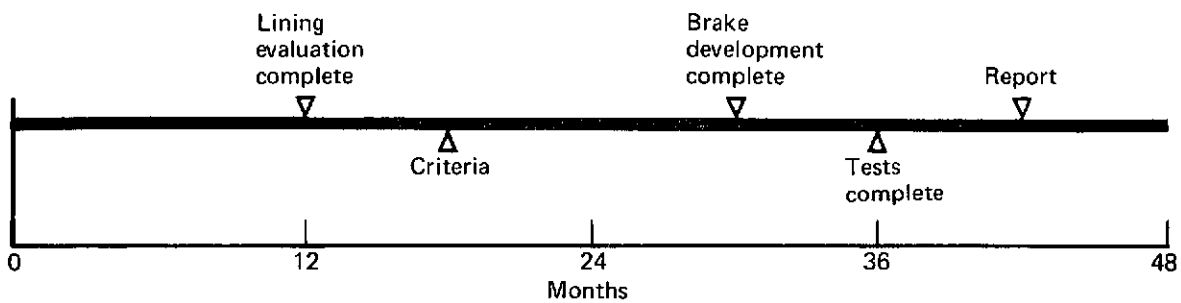
##### WORK STATEMENT

- Evaluate lining material vibration characteristics using lining test facility
- Develop analytical tool to predict impact of lining characteristics on total system
- Establish design criteria
- Develop brake system
- Test

##### PAYOFF

- Reduced landing gear vibration
- Increased deceleration rate capability
- Increased brake fatigue life

##### SCHEDULE



**FIGURE 43.—LANDING GEAR/BRAKE DYNAMICS  
RESEARCH AND TECHNOLOGY SUMMARY**

#### 4.2.5 Work Package 20—Automatic Stopping System

##### 4.2.5.1 Potential Payoff

The flow capacity of a runway can be increased severalfold, to accommodate the demands of the future, by a coordinated set of improvements in a number of airplane and airport parameters. One key factor is the ability of the airplane to decelerate on landing as quickly as the passengers and crew will tolerate to clear the runway for the next operation. To achieve the quickest deceleration to exit speed, it is necessary to apply the brakes, spoilers, and other drag devices immediately after touchdown at rates that give the desired deceleration profile. Automatic brake application and spoiler deployment devices are required to accomplish this. The airplane deceleration forces during high-speed braking are shown in figure 44.

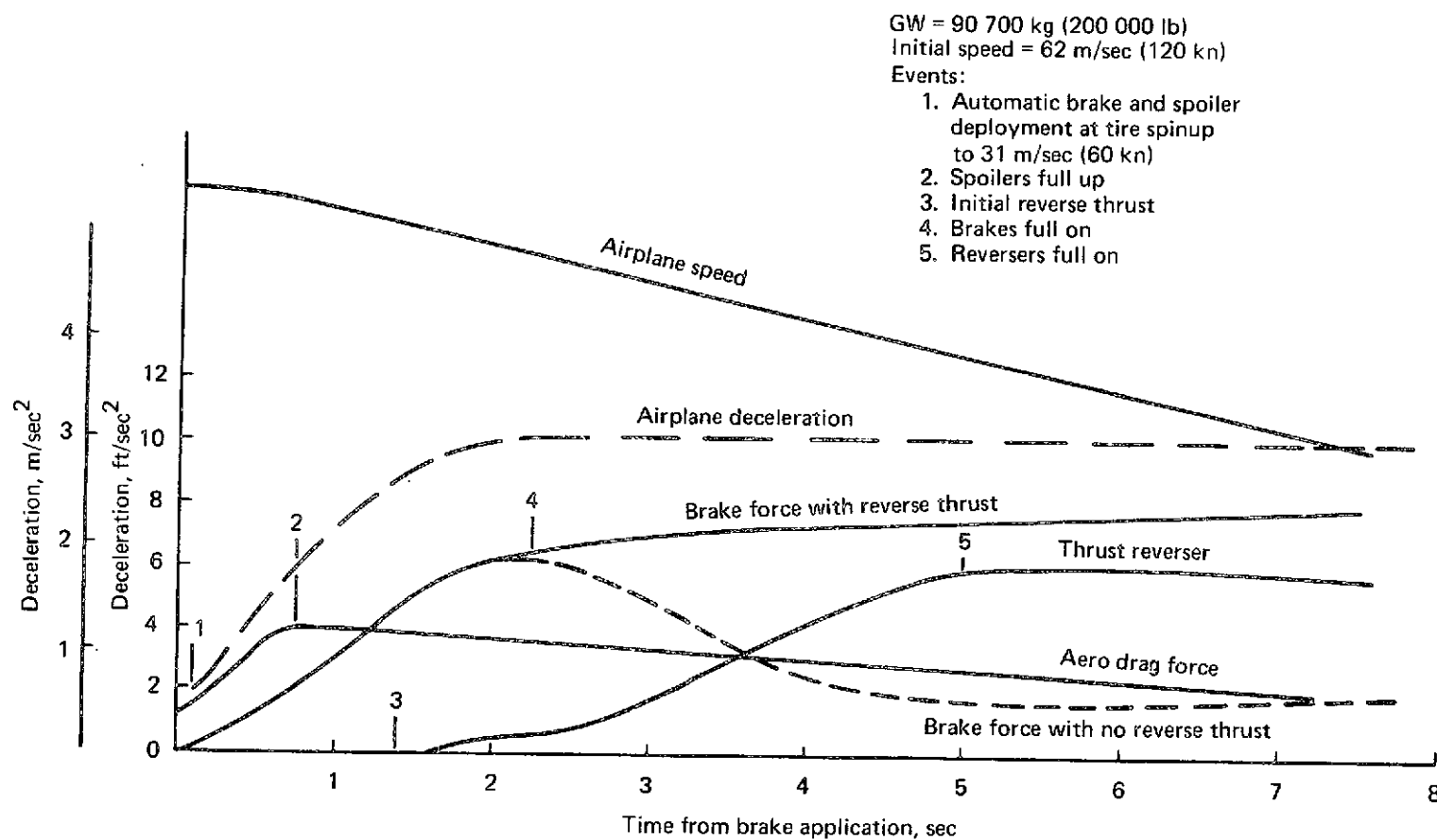


FIGURE 44.—RAPID DECELERATION SEQUENCE

It is important to accomplish spoiler deployment as quickly after touchdown as possible to dump lift and stabilize the airplane firmly on the ground. The load must be firmly established on the braked wheel at brake application to achieve smooth, comfortable deceleration. Also, deployment of spoilers and other aerodynamic drag devices early after touchdown is important to take advantage of the higher drag at high speeds. This will minimize use of wheel brakes thus reducing their weight and maintenance costs.

Braking action must be coordinated with autoland and decrab operations. The aerodynamic drag forces must be augmented by braked wheel force early in the stop to achieve the level of deceleration required for early turnoff. For passenger comfort, the brakes must be ramped on smoothly and must operate smoothly throughout the braking portion of the stop. This can only be accomplished with a good automatic brake control system.

#### 4.2.5.2 State of Readiness

Automatic braking devices are presently used on some 737 and 747 airplanes. These are first-generation systems that were added to existing brake control systems to achieve consistent early brake application with maximum comfort to the passengers. These systems perform this function very well but may not be adequate to achieve the deceleration profile required for constant early turnoff under all weather conditions. Those systems provide no differential brake control capability and are not intended as the primary brake control. The manual control system with antiskid still performs that role.

What is required for this purpose is an automatic brake control system that acts as the primary system and is integrated with the control of the spoilers, reversers, and other aerodynamic drag devices. Landing in crosswinds, on slick runways, and under other adverse weather conditions must be considered. Other control functions such as airplane derotation and rudder steering, must also be considered in the system design.

#### 4.2.5.3 Recommended Action

A multiphase development program that culminates in a flight test evaluation of the system is recommended.

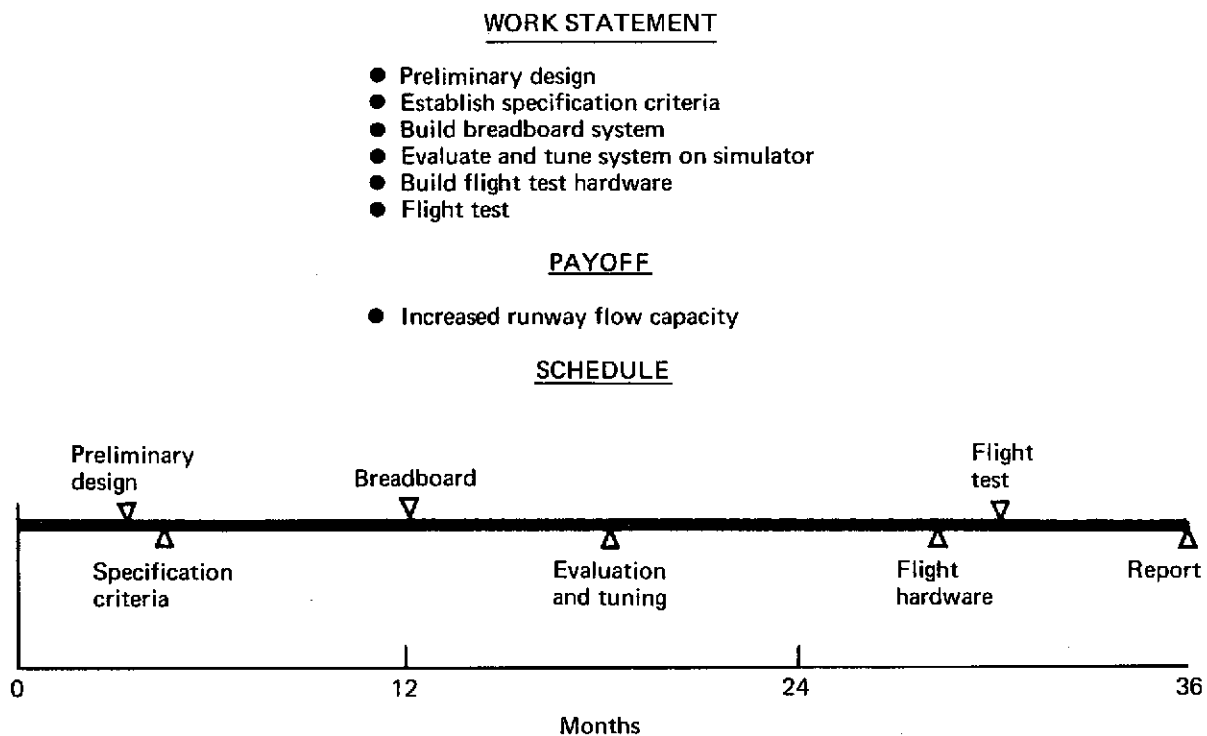
- a) Phase I—Undertake a preliminary design and analysis effort to establish design requirements. A brake control simulator would be required in this effort.
- b) Phase II—Establish a specification, accomplish hardware design, and perform qualification tests.



- c) Phase III—Build a breadboard system and evaluate and tune the system using a brake control simulator facility.
- d) Phase IV—Procure and install hardware for flight test evaluation on the RSFS. Conduct flight tests and evaluate data. A total of 15 flight-hours are required for this test.

#### 4.2.5.4 Cost and Schedule

A 3-year program plan (fig. 45) is estimated to require a total funding of \$1.5 million.



**FIGURE 45.—AUTOMATIC STOPPING SYSTEM**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.6 Work Package 21—Brake Material and Configuration

##### 4.2.6.1 Potential Payoff

The flow capacity of a runway can be increased severalfold, to accommodate the demands of the future, by a coordinated set of improvements in a number of airplane and airport parameters. One key factor is the ability of the airplane to decelerate on landing as quickly as the passengers will

tolerate to clear the runway for the next operation. The effect of high deceleration on brake life is shown in figure 46. Brakes designed for this higher energy dissipation will either be heavier and bulkier or require more frequent maintenance. Also, powered-wheel concepts are being considered that require space in the wheel, space conventionally occupied by the brake.

New brake materials and configurations are needed that will minimize the weight penalty associated with a higher capacity brake and provide space for the brake and powered-wheel equipment.

Composite carbon can fulfill a threefold purpose in a brake serving as heat sink, friction material, and structure. Thus, it permits simplicity of design and, because of its high heat capacity and higher allowable operating temperature, offers weight savings of up to 50% in the heat stack over conventional steel brakes. Another favorable factor is its low coefficient of thermal expansion which makes structural carbon immune to thermal distortion thus permitting simple, one-piece rotor and stator disc design.

Structural carbon can offer good wear characteristics when used properly. Considerably longer life could be expected in airline use and low maintenance cost should result from the less complex design.

#### 4.2.6.2 State of Readiness

Structural carbon brakes have been selected for both the B-1 and F-15 military aircraft and the British-French Concorde SST. Several brake suppliers are actively pursuing carbon brake development, and some are in limited service test on the Boeing 747 test airplane. However, the noted activity is neither adequate nor timely for commercial needs, so an expanded effort is essential. Some 737 airplanes are fitted with low-profile tires, so they would be readily adaptable as test vehicles. Ample space would be available for a larger volume brake without increasing wheel size. This probably would not be true on other airplanes where wheel wells are usually congested.

The 737 airplane also is an excellent service test vehicle because of its high frequency of operations. This provides a severe test environment for the brake and also allows for rapid accumulation of data, thus decreasing the duration of the service test.

#### 4.2.6.3 Recommended Action

A multiphase program that leads to an early in-service evaluation of a carbon brake is recommended.

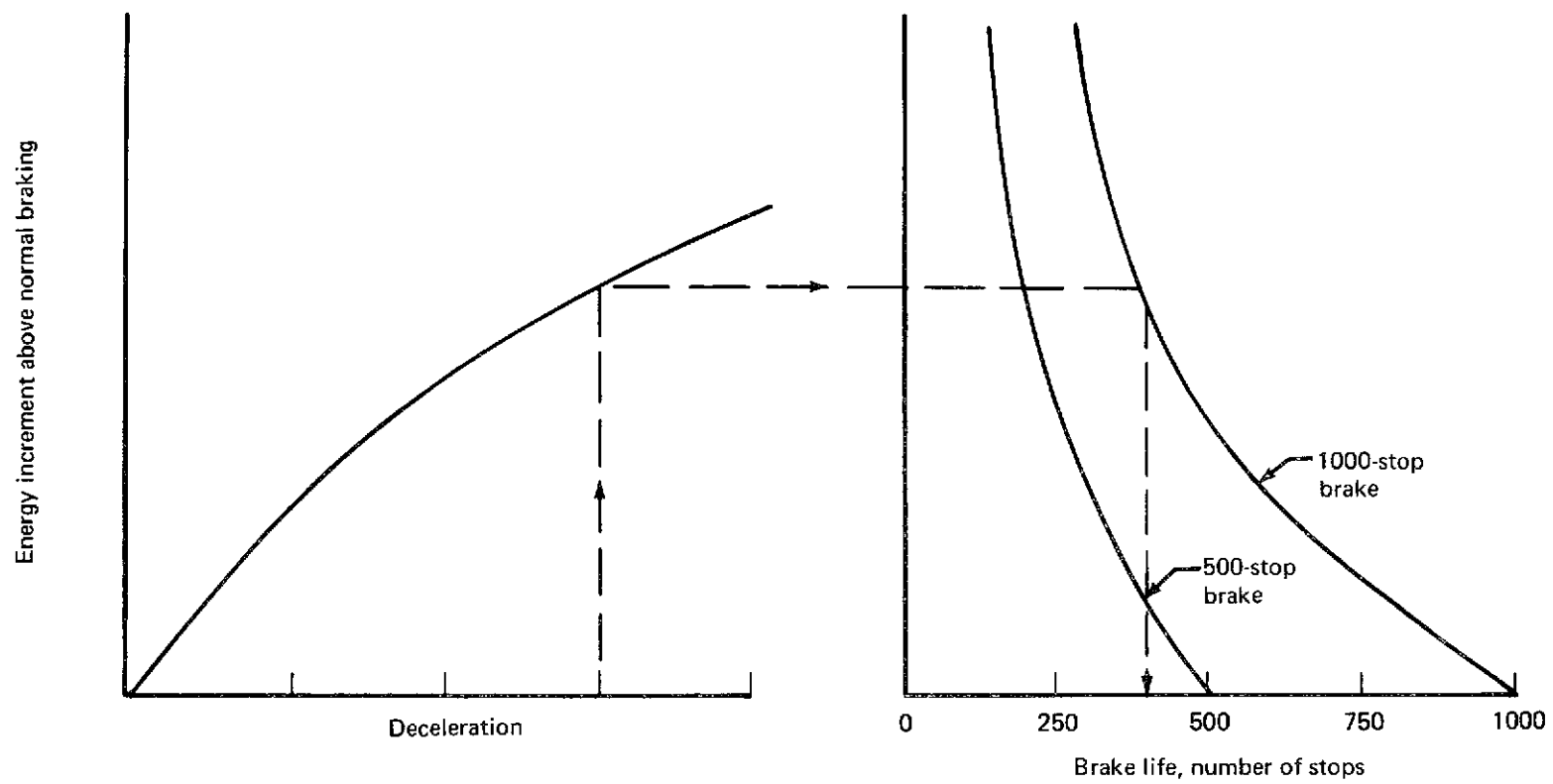
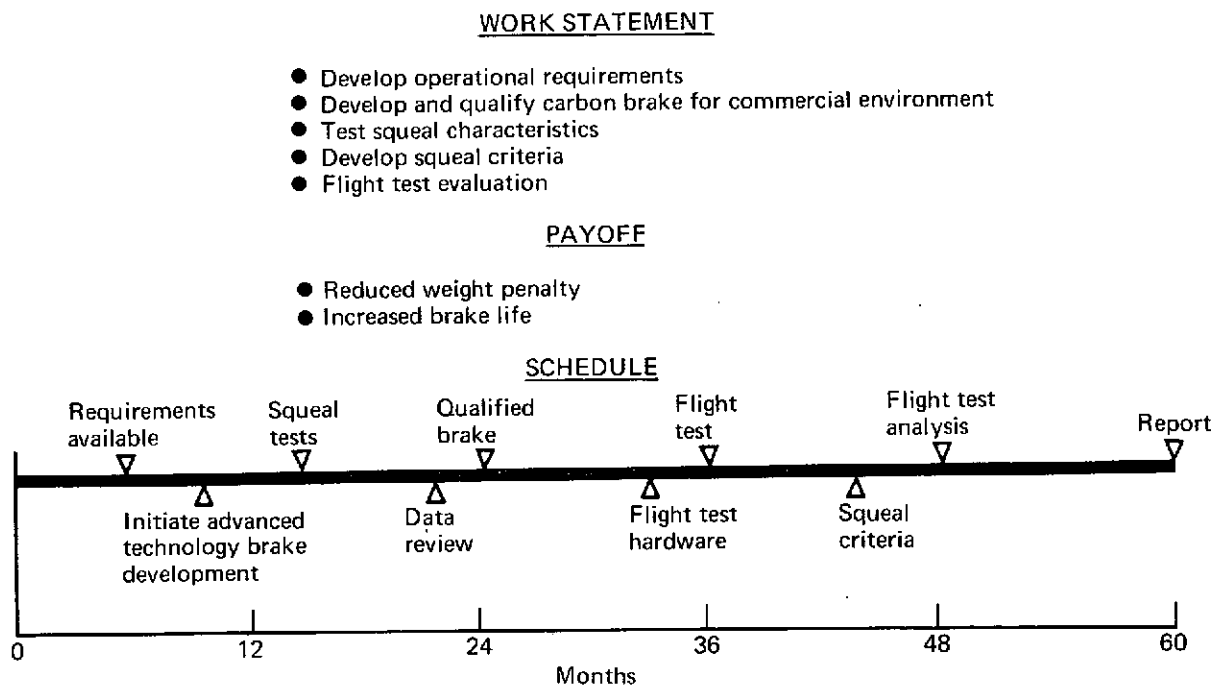


FIGURE 46.—EFFECT OF HIGH DECELERATION ON BRAKE LIFE

- a) Phase I—Carry on a 4-month preliminary design and analysis effort to evaluate and screen various supplier brake materials for minimum squeal characteristics. A lining test facility would be required for sample testing. This effort would also assist in establishing design requirements.
- b) Phase II—Establish a brake procurement specification, initiate procurement, design hardware, manufacture laboratory test hardware, and perform qualification tests.
- c) Phase III—Procure and install flight test hardware in a 737. Sufficient testing would be accomplished to permit certification for airline use.
- d) Phase IV—Procure and install hardware for an in-service 737 for airline evaluation. About 250 landings per month could be achieved; this would permit evaluation of the brake through several overhaul cycles.

#### 4.2.6.4 Cost and Schedule

The 5-year program plan shown in figure 47 is estimated to require a total funding of \$1.5 million.



**FIGURE 47.—BRAKE MATERIAL AND CONFIGURATION  
RESEARCH AND TECHNOLOGY SUMMARY**

## 4.2.7 Work Package 22—Ground Steering Systems

### 4.2.7.1 Potential Payoff

Maximum flow capacity of a runway requires minimum occupancy time by each aircraft. This objective normally requires the use of a high-speed runway turnoff or exit and a well-designed taxiway traffic system to prevent congestion on the ground that would interfere with landing operations. For maximum effectiveness in the total air transportation system, high flow rates must be feasible during adverse weather conditions that affect runway surface characteristics and visibility.

### 4.2.7.2 State of Readiness

High runway exit speeds conducive to minimum occupancy times are seldom used even during good weather conditions. Airports and airplanes have not been specifically designed to improve the total flow capacity. Present airplane and steering system designs are adequate for the required turn performance on dry surfaces but are not configured to assist the pilot during operations in adverse conditions that are considerably more critical. Pilot confidence in airplane turning performance at high ground speeds is low, partly due to lack of practice and partly due to an appreciation of the variable nature of surface friction. Considerable analytical capability exists to apply to this area; however, a pronounced lack of time test data (cornering, braking forces in various situations) hampers its application.

The problem can be solved by making a considerable improvement in the steering control capability that can be exerted on the airplane. Two general ways in which this might be accomplished are by means of automatic devices to assist the pilot and by means of changes in the weight distribution of the airplane to put more load and hence control on the nose gear. In addition, airport layouts should be designed not only with good runway exits but with optimum exit placement and with an adequate taxiway system.

### 4.2.7.3 Recommended Action

Several aspects that need evaluation and development should be accomplished in a multiphased program aimed at increasing the effective steering control available to the pilot. This will generate the capability to increase the flow capacity of airports. These efforts will require a flight test program to verify the feasibility of the selected concepts.

- a) Phase Ia—Develop and evaluate various methods for improving airplane ground control including changes in weight distribution and automatic steering devices. For the most

effective results, this step requires new tire test data that can be supplied by NASA (Langley loads track).

- b) Phase Ib—Evaluate improved runway-taxiway layouts using an existing (Boeing) real-time simulator to develop a high-capacity airport.
- c) Phase II—Develop an improved interface between the pilot and the airplane/system consistent with the requirement to minimize runway occupancy time.
- d) Phase III—Conduct pilot evaluations of the selected candidates by means of the real-time simulator to prepare for an efficient flight/ground-test program.
- e) Phase IV—Perform ground/flight test of the leading concept to establish feasibility for airline use and to demonstrate the payoffs of such concepts. This phase is expected to require 200 hr of airplane taxi tests and 50 (each) takeoffs and landings.

#### 4.2.7.4 Cost and Schedule

The program plan shown in figure 48 is estimated to cost \$1 million.

### 4.2.8 Work Package 23—Reduced Gate-Space Design Technique

#### 4.2.8.1 Potential Payoff

Improved terminal and airplane utilization will be realized by reduced airplane delay time through improved design of airplane and terminal. Present airplanes are limited by geometry considerations resulting in terminal gate spacings dictated by the size and maneuver capabilities of the airplane. A large part of the airplane and terminal design results from the evaluation of functional requirements of each taken separately, resulting in a terminal/airplane interface requiring compromise at the expense of both passengers and operators. Both airplane and terminal can be improved and the delays experienced by both customer and operators reduced.

#### 4.2.8.2 State of Readiness

We already recognize the terminal/airplane interface problem. Airplanes and terminals are already being modified for more effective utilization. However, long-range plans must be developed for future airplane and terminal design, so a plan can develop for an orderly transition into future needs. Loading and unloading of airplanes is now based on intermittent action necessitated by maneuvering an airplane into a loading stall then backing it out for its return to the runway. Gate

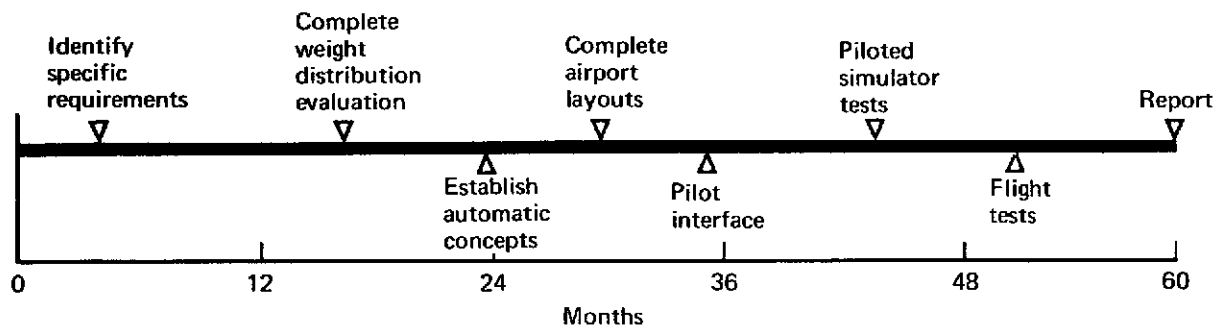
#### WORK STATEMENT

- Development and evaluate techniques—airplane control
- Develop improved runway exit
- Improve pilot interface
- Conduct piloted simulator evaluations
- Flight test

#### PAYOFF

- Increased runway flow capacity

#### SCHEDULE



**FIGURE 48.—GROUND STEERING SYSTEMS**

#### **RESEARCH AND TECHNOLOGY SUMMARY**

spacing, limited by the geometry of fixed-wing airplanes, can be reduced by variable-geometry airplanes entering the gate area with wings swept as shown in figure 49.

#### **4.2.8.3 Recommended Action**

A program to develop high-speed approach and departure by improved gate space design is recommended. We should study the terminal gate space in several phases to identify the problems and then combine those phases into the logical conclusions resulting in recommendations for better airplanes and better terminals. The system must recognize the need for airplane servicing and unscheduled maintenance before dispatch.

Reduced gate space for use of variable geometry is shown in figure 49. Subterranean distribution systems to expand airport utilization can be developed, as shown in figure 50.

- Phase I—Study current traffic loads with a projection of future loads.
- Phase II—Study ramp area delays, their cause, and impact.

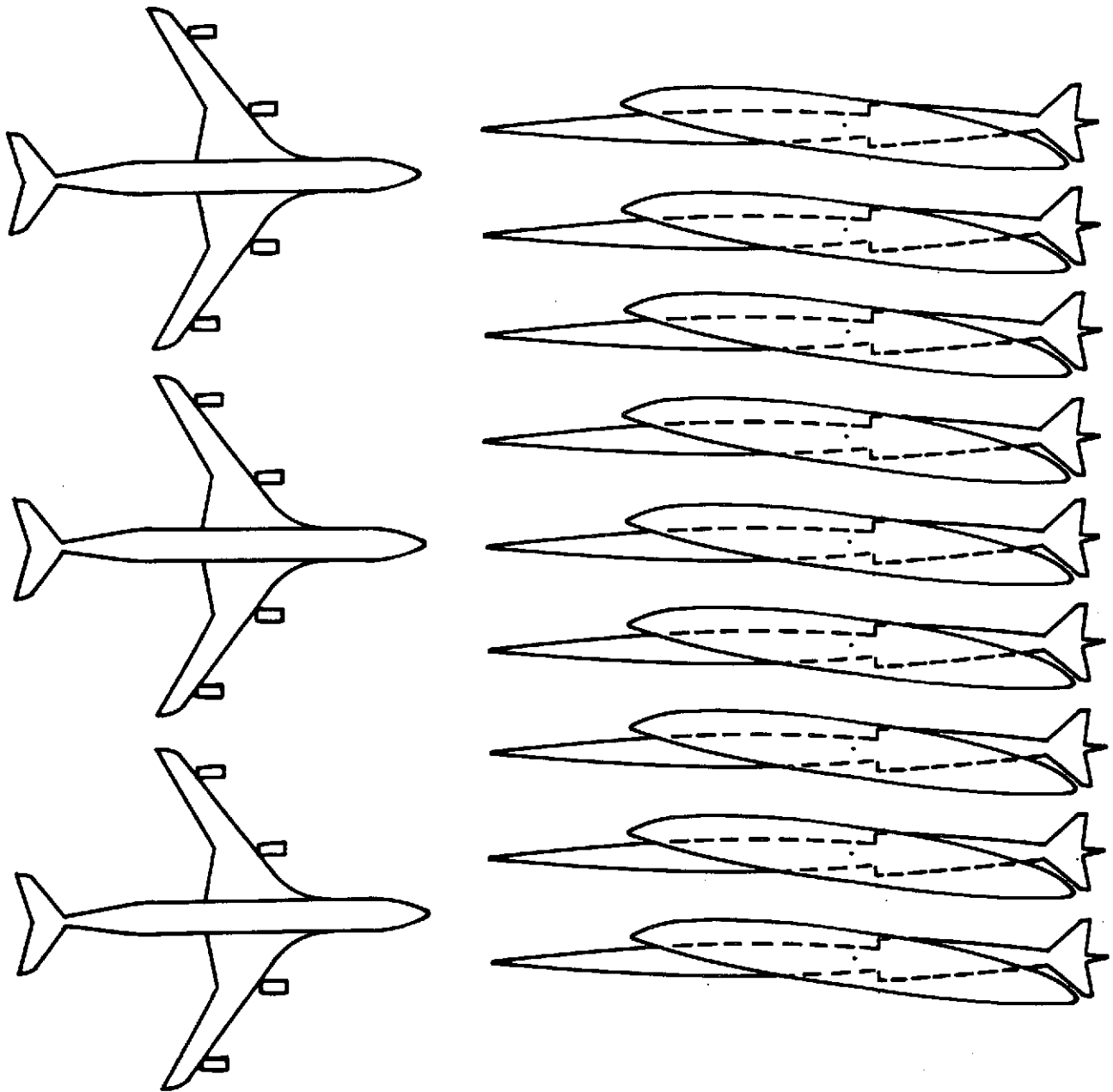


FIGURE 49.—REDUCED GATE SPACE



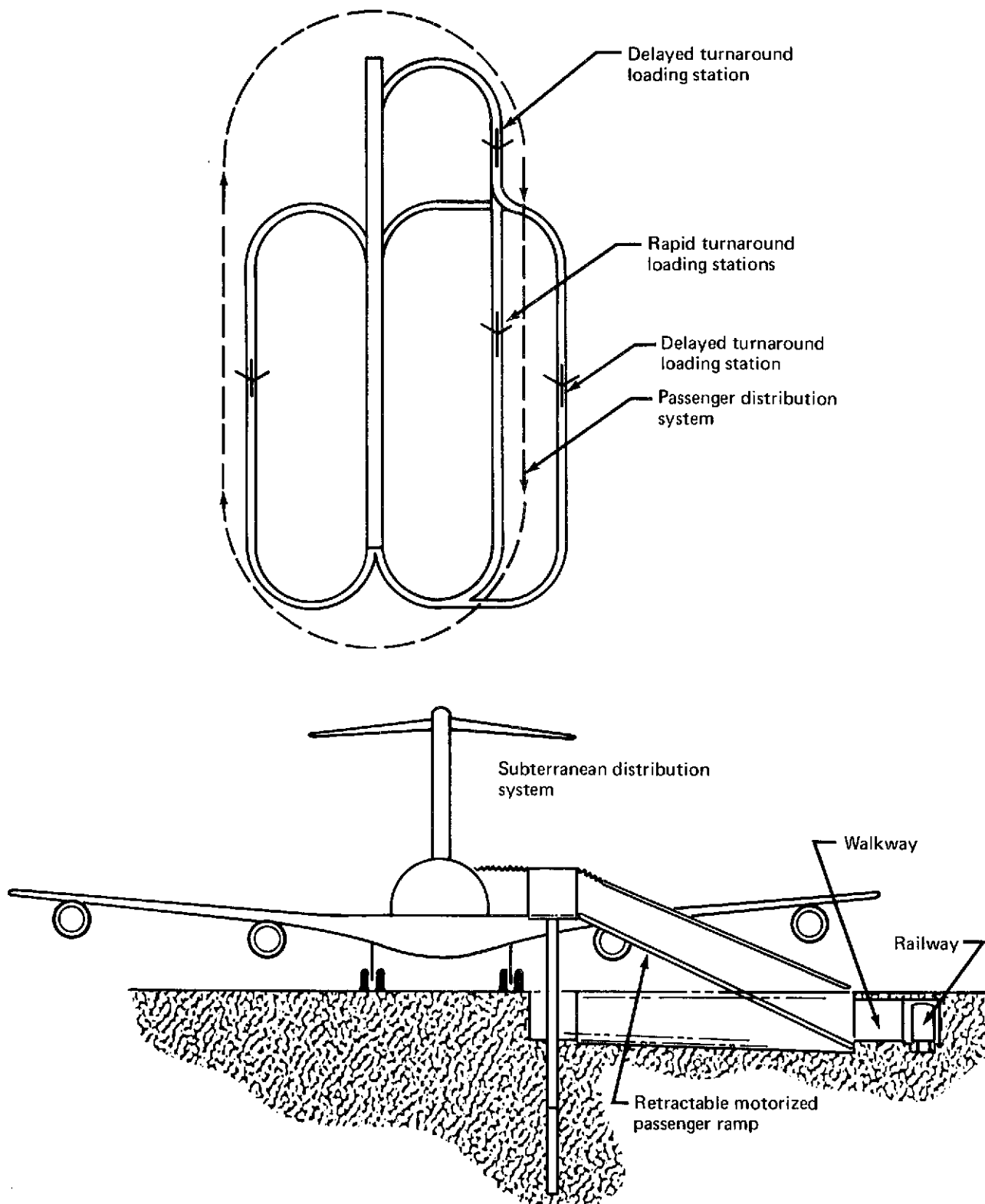


FIGURE 50.—CONTINUOUS-PASSENGER-FLOW LOADING

- c) Phase III
  - 1) Evaluate passenger handling in the terminal and project future loading objectives.
  - 2) Evaluate freight handling in the terminal and project future loading objectives.
- d) Phase IV—Evaluate airplane loading delay effects on other airplanes.
- e) Phase V—Determine requirements for better loading in future airplanes.
- f) Phase VI—Analyze the terminal/airplane combination.
- g) Phase VII—Determine an objective design approach to terminal and airplane, establishing an optimum configuration for both in terms of total system economics.
- h) Phase VIII—Determine the transitional design steps required to get from today's terminal airplane to the objective terminal airplane.
- i) Phase IX—Define a hardware program to test elements of concepts.

#### 4.2.8.4 Cost and Schedule

A 3-year plan (fig. 51) is estimated to require a total funding of \$600,000.

### 4.2.9 Work Package 24—Airframe and Engine Maintainability

#### 4.2.9.1 Potential Payoff

Maintenance costs are the single greatest part of commercial airline operating costs. Any program leading to reduced maintenance costs will have large payoff in reducing air travel expense. Maintenance labor is an ever-increasing cost item for the airlines. Automatic procedures that can be applied to large influence items of maintenance costs have potential large savings.

#### 4.2.9.2 State of Readiness

Maintenance monitors are already flying in modern aircraft. Data on performance and problems is available. Modular construction has been applied to aircraft systems including engines. Development of these concepts and expansion into other high labor cost items is within the state of the art in automation.

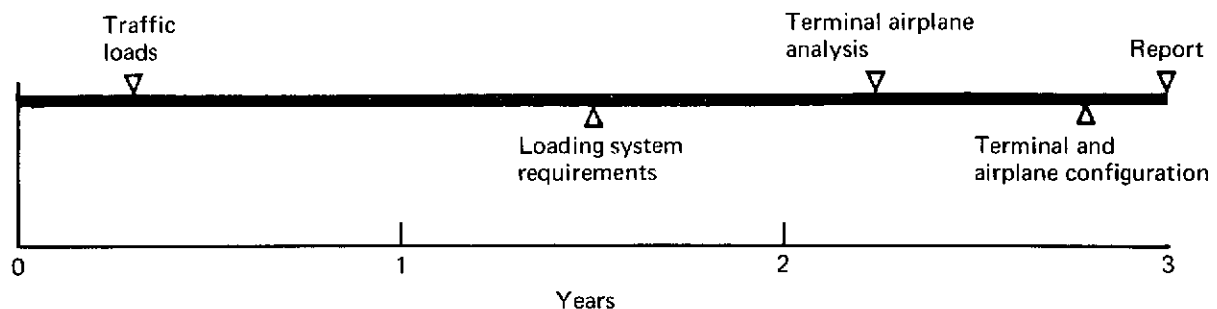
#### WORK STATEMENT

- Develop projections of future traffic loads
- Understand terminal area delays
- Understand current traffic handling and project future methods
- Determine effects of loading delays and other airplanes in terminal area
- Develop an objective terminal/airplane combination
- Develop an orderly procedure to achieve the objective

#### PAYOFF

- Better utilization of terminal facilities
- Better utilization of airplanes
- Reduced traffic delays

#### SCHEDULE



**FIGURE 51.—IMPROVED TERMINAL AND AIRPLANE UTILIZATION  
RESEARCH AND TECHNOLOGY SUMMARY**

#### 4.2.9.3 Recommended Action

The following action is recommended:

- Identify ATA systems that are large maintenance items on modern and advanced-technology aircraft.
- Identify components within such systems that have high failure rates and/or high cost of maintenance when failure occurs. Determine to the extent possible causes of failure.
- Make an intensive study of means of easy diagnosis of the failure (simple marginal process or automated test).
- Make an intensive study of the feasibility of modular construction such that simple interchange of modules could accomplish the corrective action.

- e) Evaluate the costs and benefits of the candidate modifications.
- f) Make recommendations for development of feasible modifications.

#### 4.2.9.4 Cost and Schedule

A 12-month program, shown in figure 52 and costing \$100,000, is recommended.

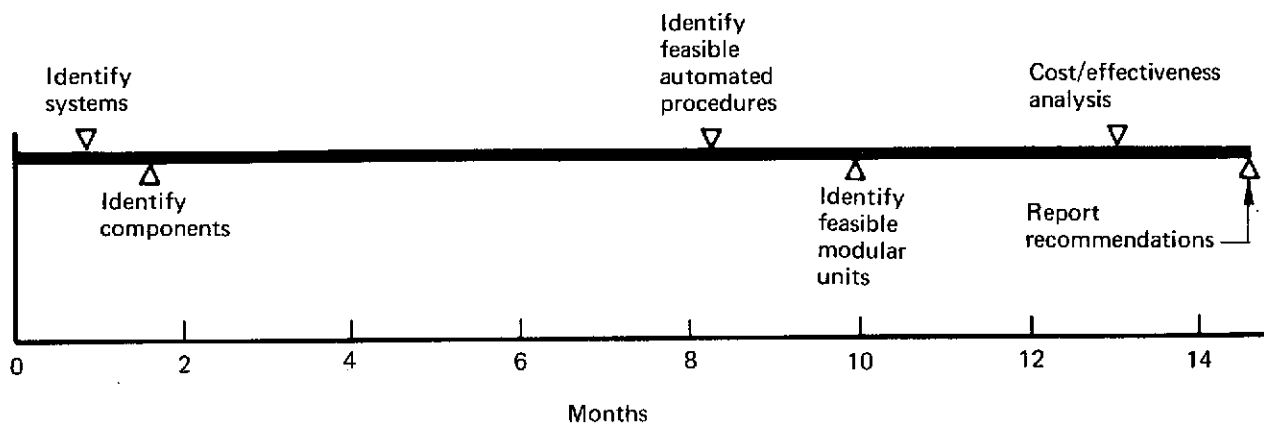
##### WORK STATEMENT

- Identify ATA systems that are high-maintenance-cost items
- Identify components within high-cost systems that have high failure rates and/or high repair costs
- Identify high labor percentage items
- Study feasibility of automated diagnostic procedures applied to this component and/or system
- Study feasibility of modular construction of this system or components of it
- Evaluate on a cost/effectiveness basis
- Recommend development of modification deemed feasible

##### PAYOFF

- Reduced maintenance costs

##### SCHEDULE



**FIGURE 52.—AIRFRAME AND ENGINE MAINTAINABILITY**

RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.10 Work Package 25—Large Payload Airplane Scheduling/Marketing Assessment

##### 4.2.10.1 Potential Payoff

Large aircraft for dense routes have the potential to not only make larger profits for the operating airlines, but also to reduce congestion in the already overcrowded airports serving large hubs. This can be accomplished by transporting larger numbers of passengers with one takeoff or landing at the busy hub than would be possible with smaller aircraft. Thus, the traffic may be transported with fewer aircraft movements. Design of an aircraft for these routes should include consideration of fuel, allowing for higher fuel prices in the future.

##### 4.2.10.2 State of Readiness

Many routes already have greater frequency than is required to serve the public (LAX-SFO, JFK-ORD, JKF-DCA, etc.). Any competitive advantage gained by adding additional service to saturated routes is generally offset by degraded economics. The increasing number of passengers can best be taken care of by some combination of higher load factors and larger aircraft. Peak-hour load factors approach 100% today on these dense routes.

##### 4.2.10.3 Recommended Action

- a) Conduct an analysis of the dense markets, including projections to the year 2000.
- b) Determine the requirements to best serve these markets including: (1) traffic requirements, (2) community noise, (3) ambient air quality standards, (4) reduction in congestion anticipated, and (5) airline operating economics with emphasis on variable fuel price.
- c) Determine the potential market for an aircraft meeting the requirements in item b above.

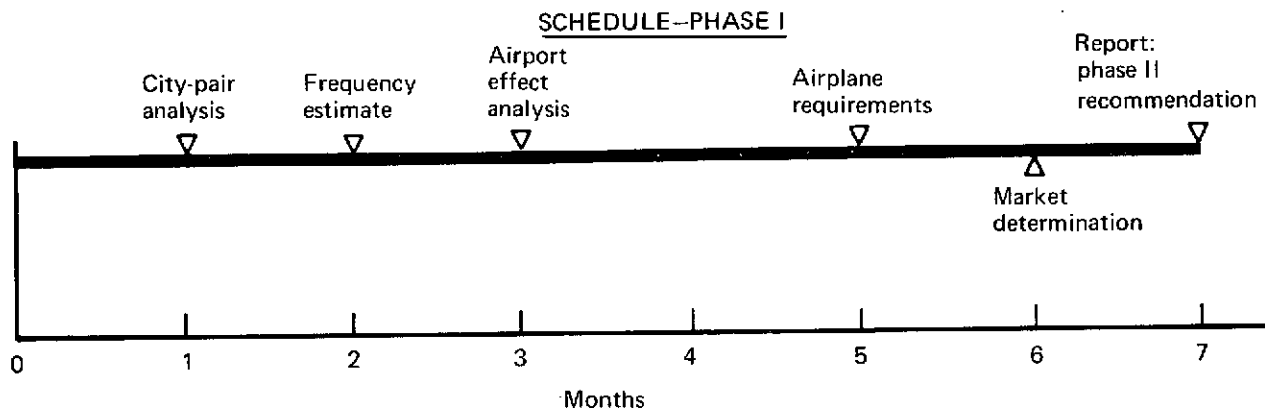
Phase II would be to configure and analyze in depth an aircraft meeting these requirements, provided the analysis in phase I indicated a potential market.

##### 4.2.10.4 Cost and Schedule

The 7-month program shown in figure 53 is estimated to cost \$50,000 for phase I.

### WORK STATEMENT

- Phase I
  - Expand passenger forecast of contract NAS1-12018 to include all city-pairs having 25 or more frequencies per day in 1972
  - Estimate frequencies per day necessary to adequately serve the demand
  - Estimate for airports involved:
    - Delay
    - Community noise levels
    - Ambient air quality in vicinity of airport
  - Develop requirements for large-payload aircraft to serve these routes:
    - Payload/range
    - Operating economics including fuel consumption and fuel price variables
    - Noise and emission characteristics
  - Determine potential market for such an aircraft
- Phase II
  - Configure and analyze in depth a large-payload aircraft, provided phase I analysis indicates a market



**FIGURE 53.—LARGE PAYLOAD AIRPLANE SCHEDULING/MARKETING ASSESSMENT**

### RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.11 Work Package 26—Aircraft Maintenance Monitor

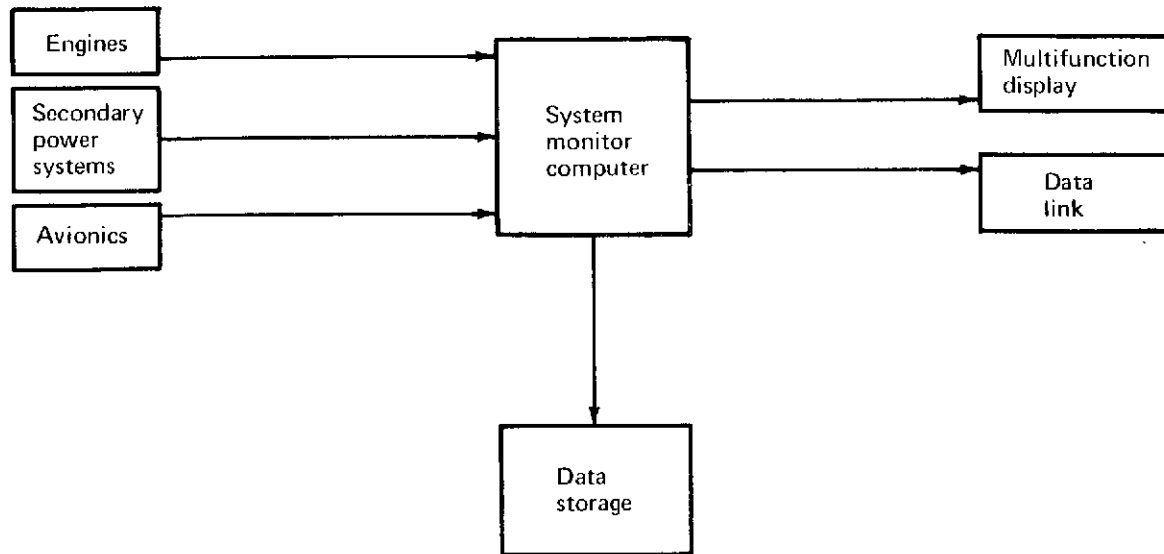
##### 4.2.11.1 Potential Payoff

The cost of repairing failed equipment; airplane time lost and schedule disruption due to unscheduled maintenance; the time spent removing, checking, and replacing suspected equipment; and scheduled preventive maintenance are all major expenses in airline operations. Better prediction of failures and identification of failed components would appreciably reduce this cost.

##### 4.2.11.2 State of Readiness

System are in use that use a central computer to keep track of failures as indicated by failure detection devices built into units, to identify units which have outputs outside tolerances, and to

provide data for ground-based trend monitoring for failure prediction as shown schematically in figure 54. Some work has been done on methods of designing equipment for better failure prediction.



*FIGURE 54.—MAINTENANCE MONITOR SYSTEM*

#### 4.2.11.3 Recommended Action

A program consisting of analysis, system synthesis, and testing of selected devices is recommended. A thorough analysis of failure modes, means of monitoring for failures and incipient failures, and statistical value of feasible levels of improvement would be made. Based on these data, an integrated system approach to the design of a monitor system, specification of airplane equipment for ease of monitoring, and maintenance procedures would be developed. Key hardware items, particularly novel physical changes to airplane equipment for incipient failure detection, would be built and tested.

#### 4.2.11.4 Cost and Schedule

The first two phases would be of 1-1/2 years duration and cost \$500,000. The third phase cost and duration would depend on the results of phase II. The program plan is shown in figure 55.

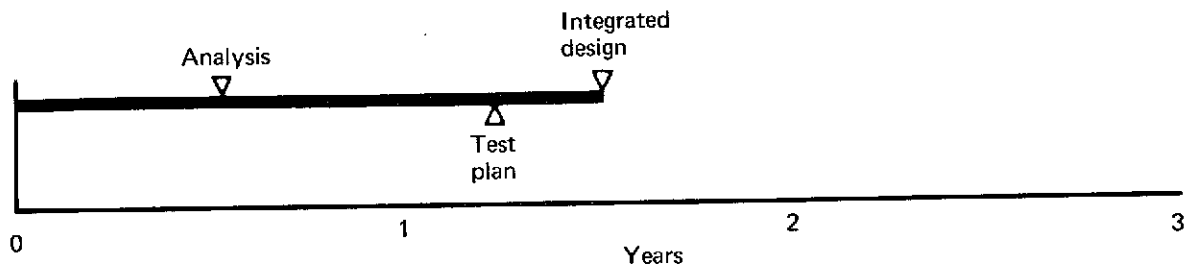
#### WORK STATEMENT

- Perform failure mode analysis
- Monitor incipient failures
- Perform monitoring value analysis
- Integrate system design
- Develop test plan
- Develop test program

#### PAYOFF

- Less unscheduled maintenance
- Fewer unjustified removals
- Less preventive maintenance

#### SCHEDULE



**FIGURE 55.—MAINTENANCE MONITOR**  
RESEARCH AND TECHNOLOGY SUMMARY

### 4.2.12 Work Package 27—Powered-Wheel System

#### 4.2.12.1 Potential Payoff

Development of a powered-wheel system (illustrated in figure 56) to provide ground maneuver capability without the use of main engines or tow tugs has several benefits. Ground air pollution would be reduced 65% to 80%. Ground noise could be reduced up to 7 dB (aft) and 30 dB (forward) when measured on the A-scale at 61 m (200 ft) radius. Elimination of the jet wake in the terminal area would be a very positive safety benefit. Preliminary study shows that reductions in ground operation costs (reduced ground equipment and taxi fuel) of the order of \$30,000 per airplane per year could be expected to offset costs of a powered-wheel system; however, some weight penalty would be expected.

#### 4.2.12.2 State of Readiness

The conceptual studies indicate that the system is technically feasible. However, its practical application requires study to determine specific methods and a more precise understanding of its effects on airplane design and airline economics.



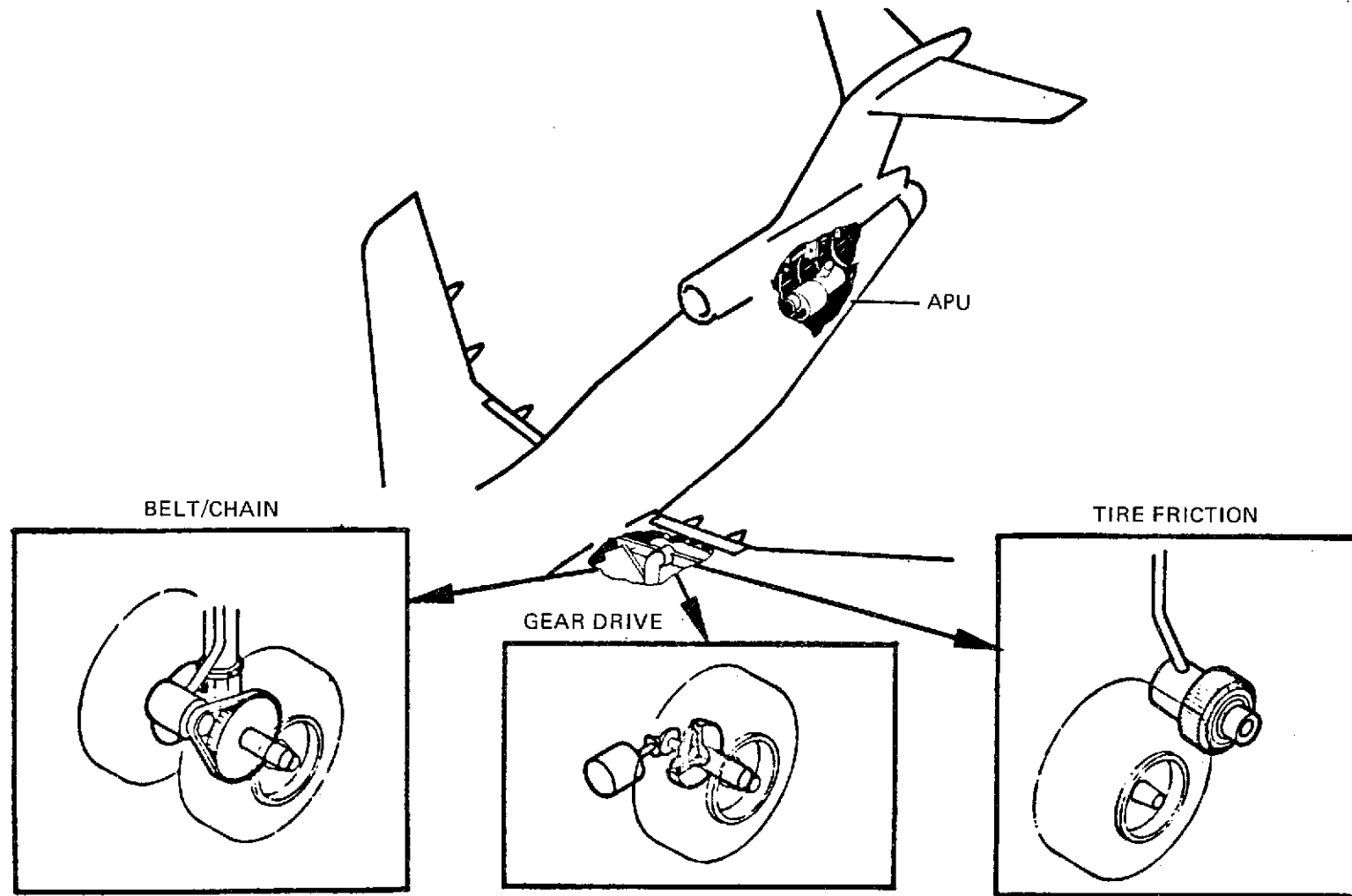


FIGURE 56.—POWERED-WHEEL CONCEPT

#### 4.2.12.3 Recommended Action

A three-phase approach is recommended, with each succeeding phase dependent upon results of the completed phase. The first phase would be a 1-year study and should include participation of two or three suppliers active in design of hydraulic, pneumatic, and electrical hardware and involvement of one or more airlines in determination of economic potential.

Phase I results would be a definite decision as to the practicality of powered landing gear wheels and a recommendation as to the advisability of investigating nonairborne ground maneuver systems.

If phase I proves continuation of the powered wheel to be advisable, hardware development and demonstration would follow. A 737 is a practical vehicle for use as a demonstrator. The torque and horsepower requirements are not extremely high, the landing gear is a relatively simple tricycle type, a suitable auxiliary power unit is available, and the airplane operating cost is low.

#### 4.2.12.4 Cost and Schedule

The initial study phase is estimated to cost approximately \$200,000 over a 1-year period. The total program estimated cost is \$1.4 to \$2.6 million over a 3-year period. The plan is shown in figure 57.

### 4.2.13 Work Package 28—Innovative Landing Gear Concepts

#### 4.2.13.1 Potential Payoff

Benefits similar to powered wheels would result if the drive mechanism can be separated from the landing gear and incorporated in some other manner, such as air cushions, extra traction wheels, etc., and problems related with main gear and brake design as well as stowage can be eased. A typical air cushion landing system schematic is shown in figure 58.

#### 4.2.13.2 State of Readiness

Preliminary studies have been conducted on use of air cushions, taxi on fewer engines, and other means of doing the powered-wheel functions. These concepts, except for taxi on fewer engines, should be explored more fully to determine if they are feasible.

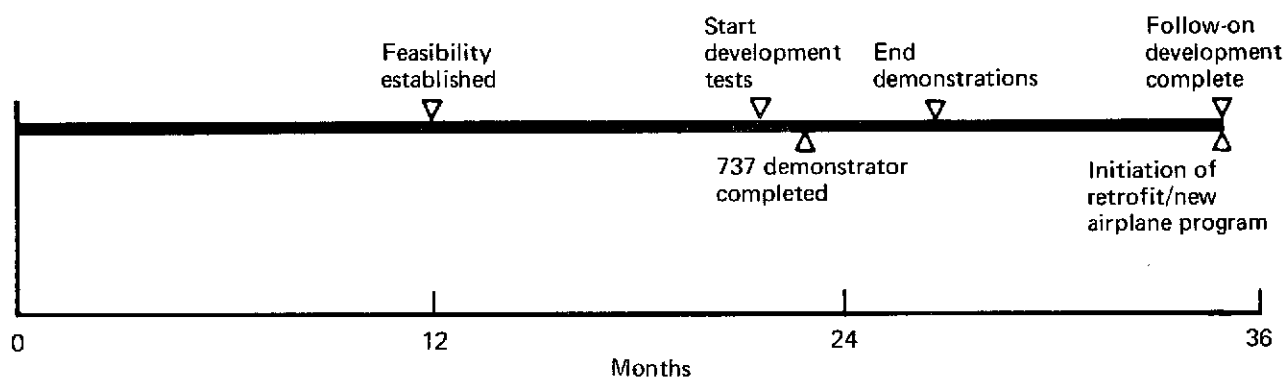
### WORK STATEMENT

- Phase I
  - Determine economic potential in industry (airlines, suppliers, and airplane companies)
  - Define required hardware
- Phase II
  - Develop hardware
- Phase III
  - Demonstration flight test

### PAYOFF

- Reduced ground operation costs
- Reduced airport pollution
- Reduced ground noise
- Elimination of jet wakes at terminals
- Improved airplane ground maneuver capability
- Reduced brake wear

### SCHEDULE



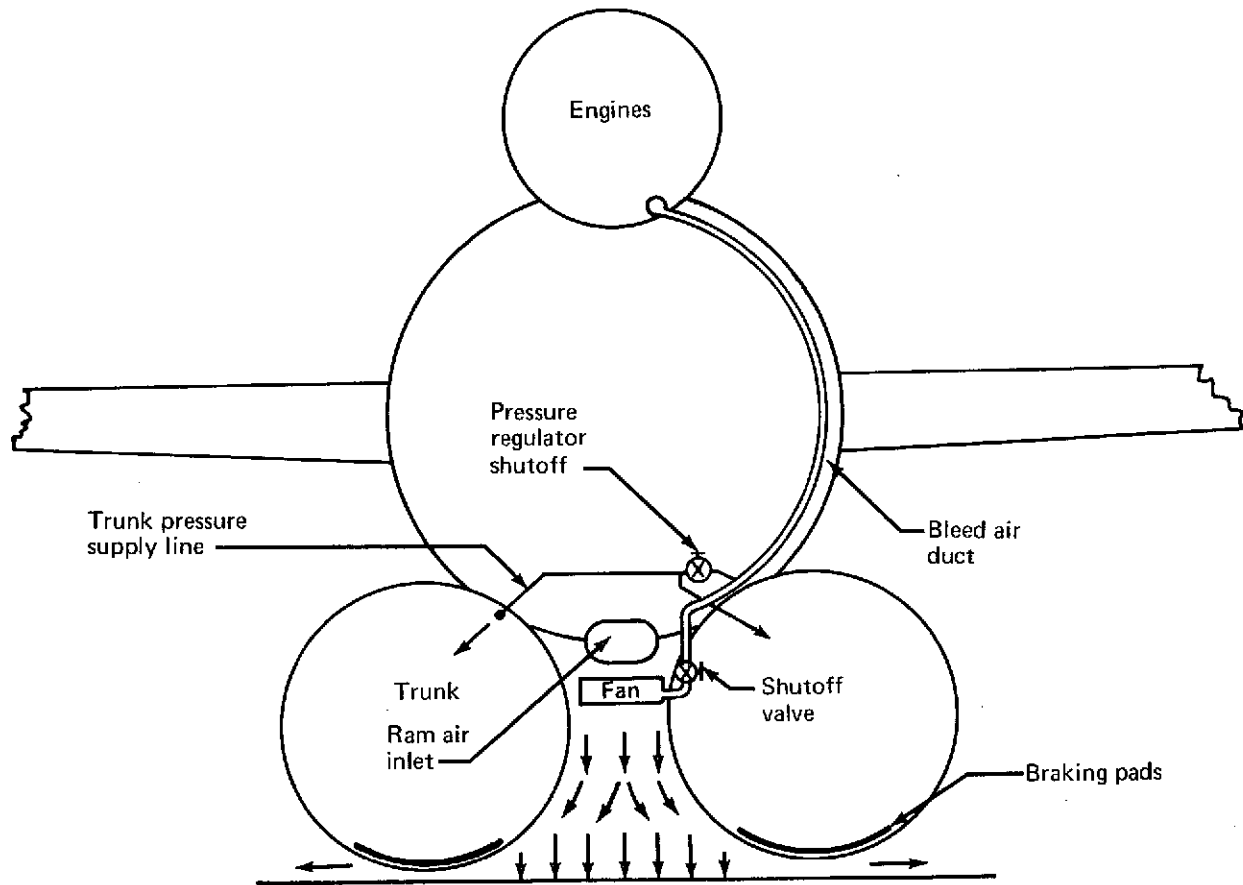
*FIGURE 57.—POWERED-WHEEL SYSTEM*

### RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.13.3 Recommended Action

A two-phase program is recommended. The first phase would require 1 year and \$100,000 funding. This phase would consist of an analytical study to evaluate candidate systems and recommend a follow-on program for development of the most promising concept.

Phase II would consist of the design, development, and testing of the recommended concept. Time required and costs of phase II would be established at the end of phase I.



**FIGURE 58.—TYPICAL AIR CUSHION LANDING SYSTEM SCHEMATIC REPRESENTATION**

#### 4.2.13.4 Cost and Schedule

The cost of the program shown on figure 59 is not expected to exceed \$300,000 nor take longer than 3 years to complete.

#### 4.2.14 Work Package 29—Powered-Wheel Operational Assessment

##### 4.2.14.1 Potential Payoff

Ground operation of aircraft with powered wheels could lead to reductions in ground handling equipment required and total fuel used. Operation with powered wheels would also result in lower emission levels. Typical ground operations currently employing the main engines that could be replaced by use of the powered wheel are shown in figure 60.

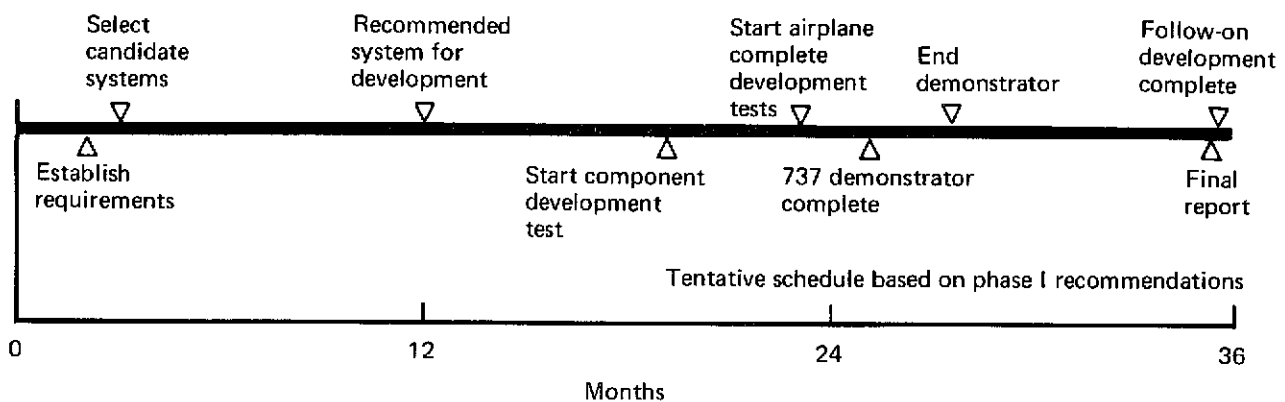
#### WORK STATEMENT

- Phase I
  - Select and evaluate candidate systems
  - Recommend concept for development
- Phase II
  - Develop hardware
  - Demonstration test

#### PAYOFF

- Minimized stowage space requirements
- Less complex landing gear than powered-wheel system

#### SCHEDULE



*FIGURE 59.—INNOVATIVE LANDING GEAR CONCEPTS*

#### RESEARCH AND TECHNOLOGY SUMMARY

##### 4.2.14.2 State of Readiness

Studies conducted evaluating powered wheels indicate possible reductions in emissions (CO and HC) produced and fuel required. These studies included assumptions, however, that have not been substantiated by present engine operation. Among these assumptions are reducing engine warmup and cool-down times, engine starting with a tailwind condition, and additional monitoring requirements for fire safety during ground starts on the taxi strip.

An EPA advance notice of rulemaking has been received proposing to taxi the airplane with two engines and start the main engines just prior to takeoff. The previously stated considerations exist if the airplane is operated with powered wheels as if the ground operating procedures are revised.

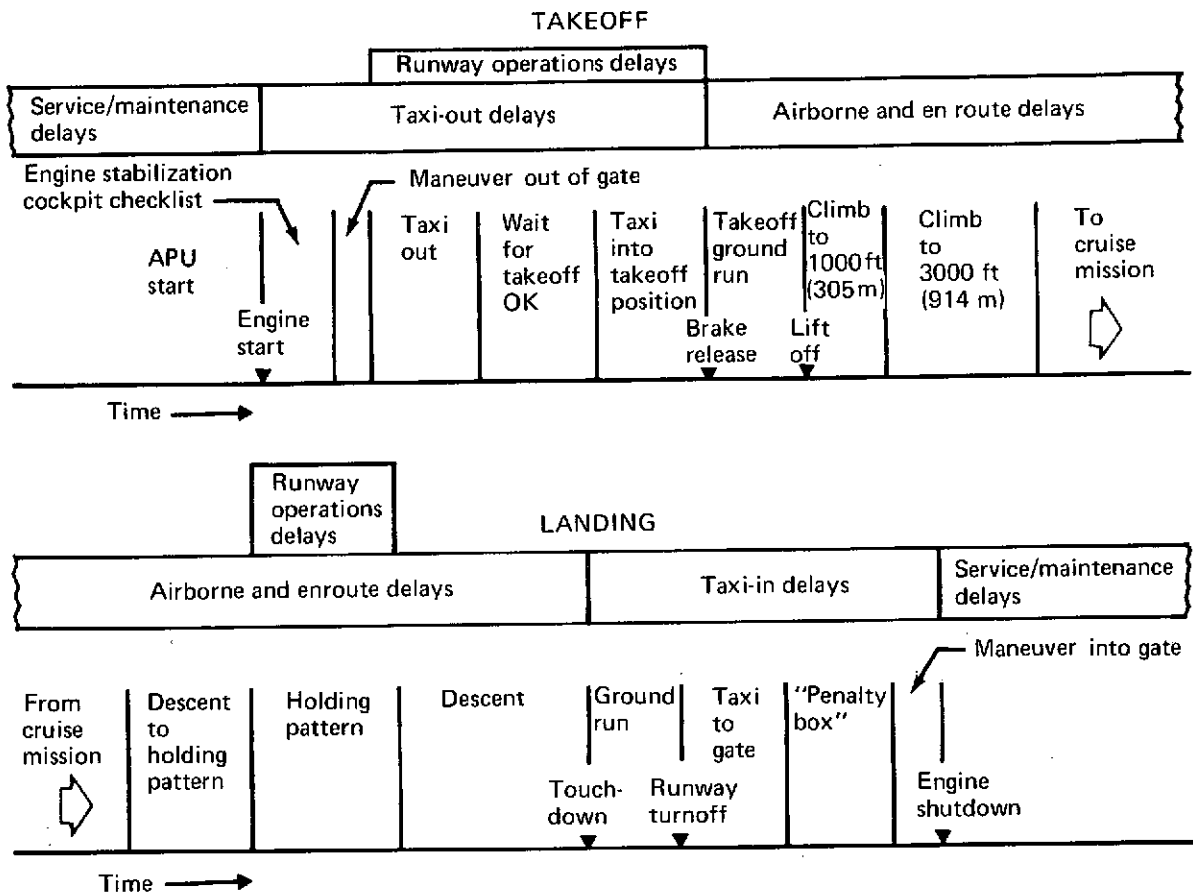


FIGURE 60.—TAKEOFF/LANDING OPERATIONS

#### 4.2.14.3 Recommended Action

A study should be initiated to identify and evaluate engine-related problems during powered-wheel operation. This study should include the following items and should be coordinated with airline operations:

- a) Reduced engine warmup and cool-down times
- b) Engine starting with a tail wind
- c) Additional monitoring during ground starts on taxi strip
- d) Engine start malfunctions at end of runway.

#### 4.2.14.4 Cost and Schedule

The 8-month program (fig. 61) is estimated to require a total funding of \$100,000.

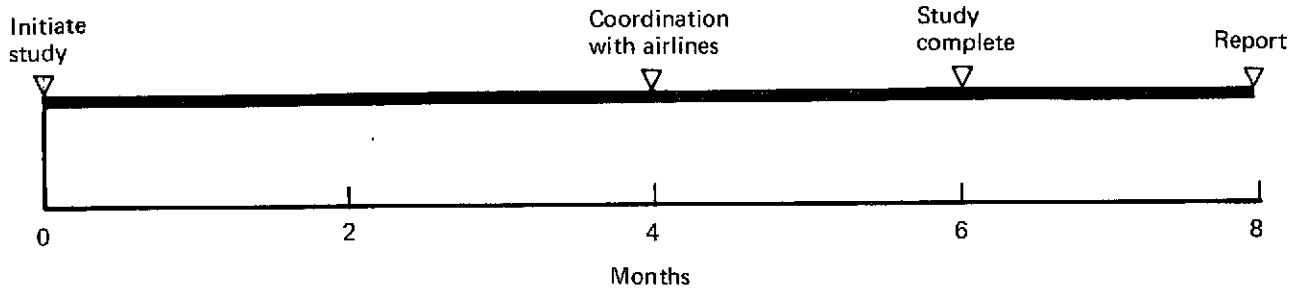
#### WORK STATEMENT

- Study to identify and evaluate problems
- Coordinate with airline operations

#### PAYOFF

- Reduced ground equipment
- Reduced fuel used
- Reduced emission levels

#### SCHEDULE



**FIGURE 61.—POWERED-WHEEL OPERATIONAL ASSESSMENT  
RESEARCH AND TECHNOLOGY SUMMARY**

#### **4.2.15 Work Package 30—Surface Traffic Control**

##### **4.2.15.1 Potential Payoff**

The high operations rates forecast at major hubs place an increasing burden on the taxiway systems of the large airports. The ground guidance problem is especially critical when poor visibility conditions exist. The capacity of the taxiway system could become a constraining element.

To examine the requirements for alternative concepts that would allow each airplane to exit the runway at high speed and decelerate and taxi to the gate safely and efficiently, a research and development program is required beginning with taxiway capacity studies and computer simulation and culminating in a test and implementation program of a ground guidance system.

##### **4.2.15.2 State of Readiness**

The present surface traffic control system is manual using visual sensors; radar (ASDE) is used in poor visibility. The surface traffic control system elements are shown in figure 62. The Department of Transportation is conducting and sponsoring programs on existing ground control and guidance systems and study, followed by the design, development, test, and evaluation of a new system for handling and guiding aircraft on the ground, the new airport surface traffic control system (ASTC).

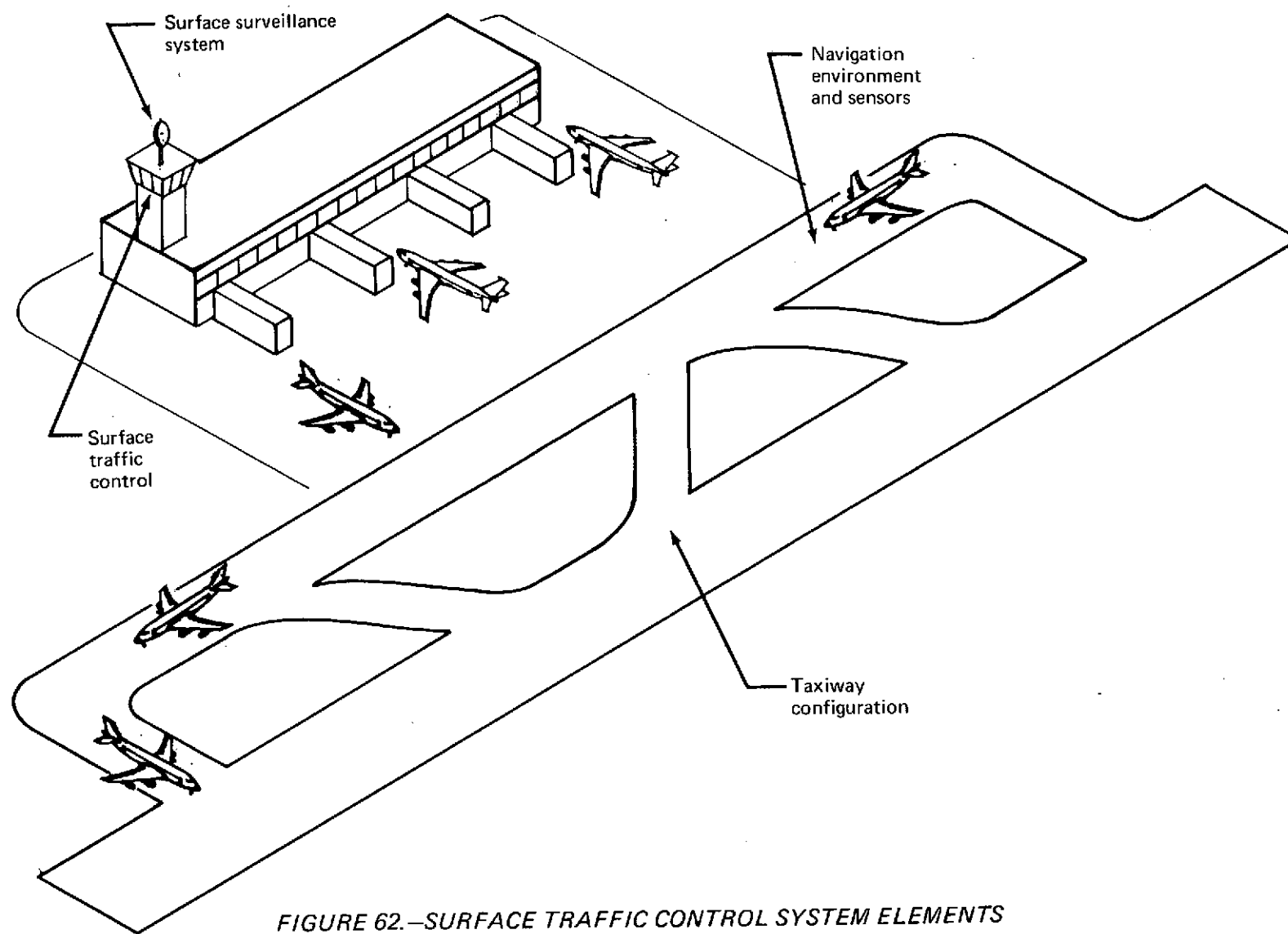


FIGURE 62.—SURFACE TRAFFIC CONTROL SYSTEM ELEMENTS



These programs deal with design and development of an interim manual system based on position surveillance, traffic flow display at the tower, light signal control from tower, and visual runway/taxiway guidance. The follow-on system includes a higher degree of automation and integration of the ground guidance and control function with approach/departure airspace control and will require improvements in surveillance, guidance, and control subsystems. Potential means of providing the new system being investigated include enhanced radar presentations and magnetic loops installed in runway/taxiway surfaces.

Consideration is also being given to the possible use of the air traffic control radar beacon system and/or the discrete address beacon system to assist in the surveillance of aircraft on the ground.

Completely automated and integrated ground traffic control systems using aircraft surveillance information from a variety of sources are being considered to control taxiway intersections. Human controllers and improved signs/signals at intersections are also being considered to supplement aircraft sensors and other hardware.

A significant parameter apparently not being studied as a variable for optimization is aircraft performance as related to movement on the airport surface.

#### 4.2.15.3 Recommended Action

Institute a research program to define the airplane navigation, guidance, and performance requirements for optimal movement on the airport surface. The program recommended consists of the following four phases:

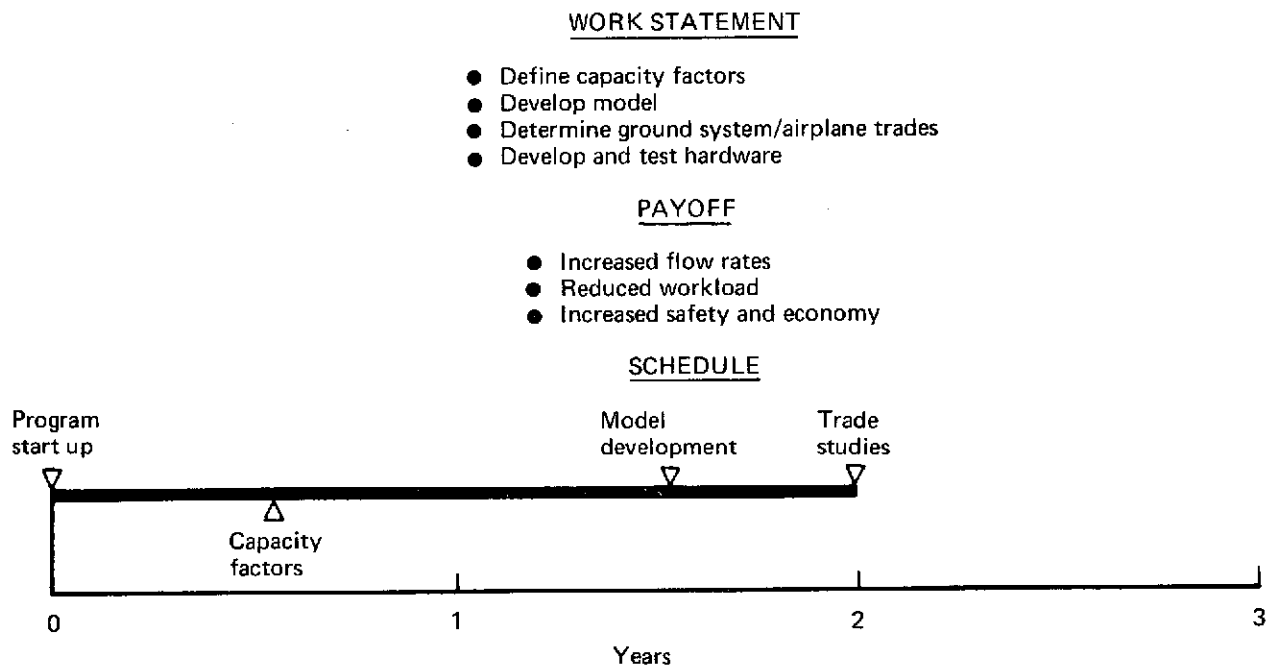
- a) Phase I—Define taxiway capacity and analyze factors.
- b) Phase II—Define, develop, and verify simulation model.
- c) Phase III—Trade study surface movement navigation, guidance, and vehicle performance.
- d) Phase IV—Test and implement selected concept.

An initial analysis has been carried out of the first two phases. Critical terms have been defined, relevant factors noted, and a preliminary flow model developed. Conclusions from the model indicate spacing control on input is required especially when demand profile peaks exceed 15% of taxiway steady-state capacity, as defined. The model developed is parametric in nature and requires data describing the velocity/density relationship for various taxiways and conditions. The

recommended source of such data is a proposed simulation explicitly relating taxiway configuration, ground guidance system, control concept, and aircraft characteristics. An estimate of the cost and schedule of these first three phases follows. The remaining phases can be detailed following completion of phase III.

#### 4.2.15.4 Cost and Schedule

The first three phases (fig. 63) would be of 2 years duration and cost \$700,000.



*FIGURE 63.—SURFACE TRAFFIC CONTROL*  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.16 Work Package 31—Passenger Tolerance

##### 4.2.16.1 Potential Payoff

High flow capacity of airports requires minimum runway occupancy time for each airplane. The limits on rapid deceleration and turnoff, to achieve the low occupancy time, are set by the accelerations acceptable to the passengers rather than by the airplane itself. Maximum flow capacity is dependent on knowing what factors influence passenger acceptance of high accelerations and what acceptable levels are.

#### 4.2.16.2 State of Readiness

Design criteria for highways, rapid transit vehicles, and other people-carrying devices are not consistent with each other and may not be directly applicable to the specific maneuvers envisioned for airplane passengers.

Experience with the Morgantown personal rapid transit system has provided partial data that can be readily applied to an airplane passenger seat, as shown in figure 64. Airplane ride comfort analysis data are available from many sources such as the ride comfort study completed for the 2707-300 SST airplane (ref. 3).

#### 4.2.16.3 Recommended Action

A program of testing subjects to determine their tolerance is recommended. Tools would include limited-motion simulators and special test vehicles. The effects of seat design, restraint devices, and visual and aural cues on acceptability of longitudinal and lateral acceleration would be determined.

#### 4.2.16.4 Cost and Schedule

This program (fig. 65) would last 2 years and would cost \$900,000.

### 4.2.17 Work Package 32--Schedule Spreading Incentives

#### 4.2.17.1 Potential Payoff

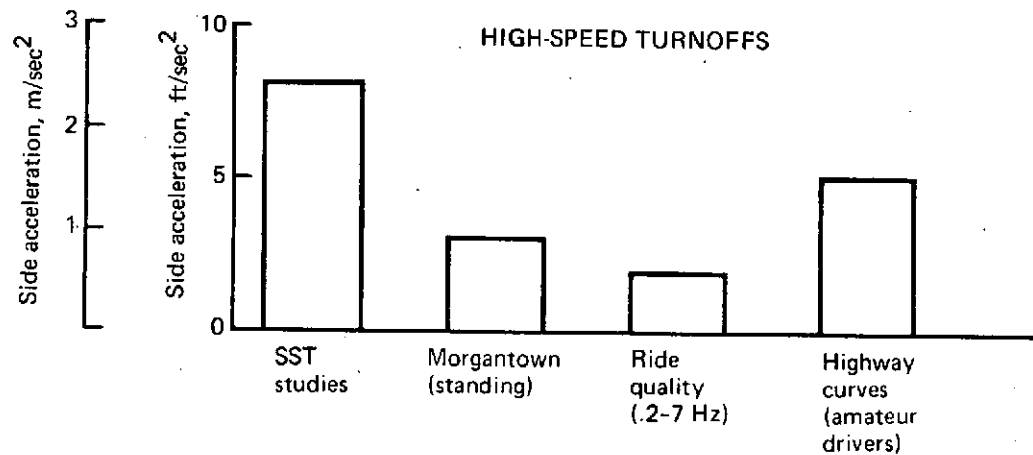
Peak-hour aircraft movements have already reached the point of saturating major hub airports, thereby making efficient, economical service impossible at these times and places. At other times of the day and week, the same airports have nominal traffic that does not tax the capacity of the airport. A number of passenger fare incentive plans have been tried to encourage travel at off-peak hours. Any systems that would spread aircraft movements more evenly throughout the day and among the days of the week would have great potential payoff in terms of airline economics (costs of delay) and in passenger convenience. The most important payoff would be in terms of efficient use of airport facilities.

#### 4.2.17.2 State of Readiness

Airlines cannot initiate a system that inhibits their ability to offer service at the time passengers want to fly. The airlines will insist on their judgement of passenger demand being the

Target

Today



Target

Today

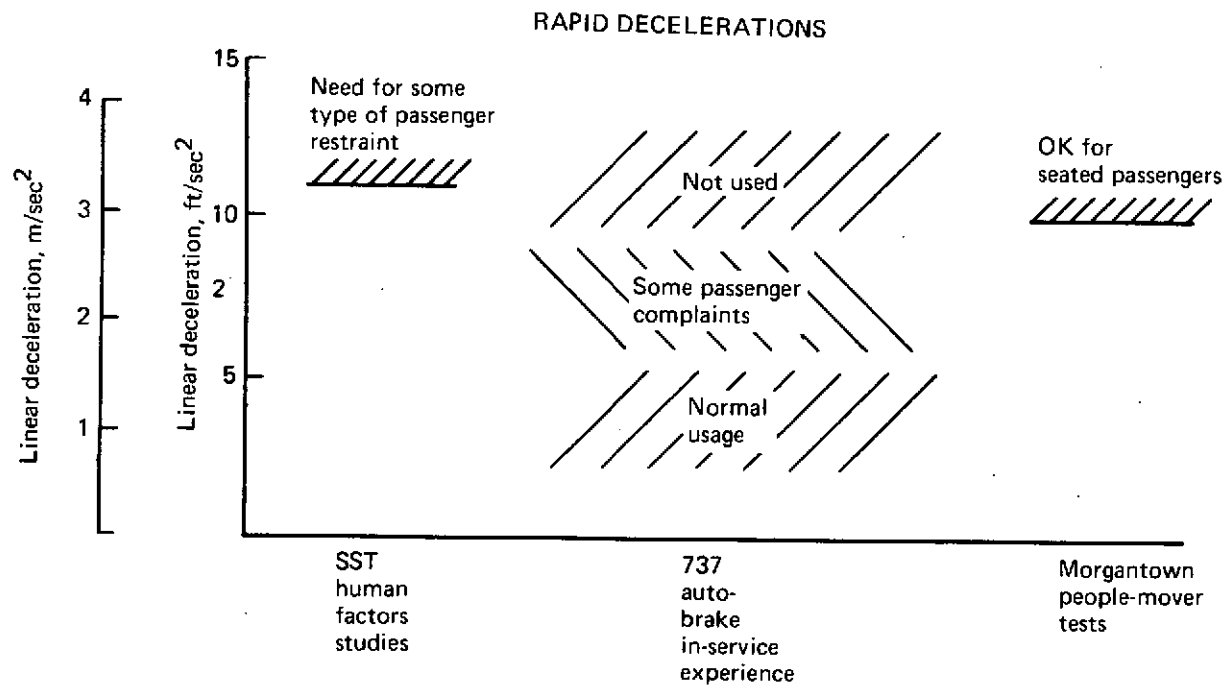


FIGURE 64.—PASSENGER ACCELERATION TOLERANCE DATA

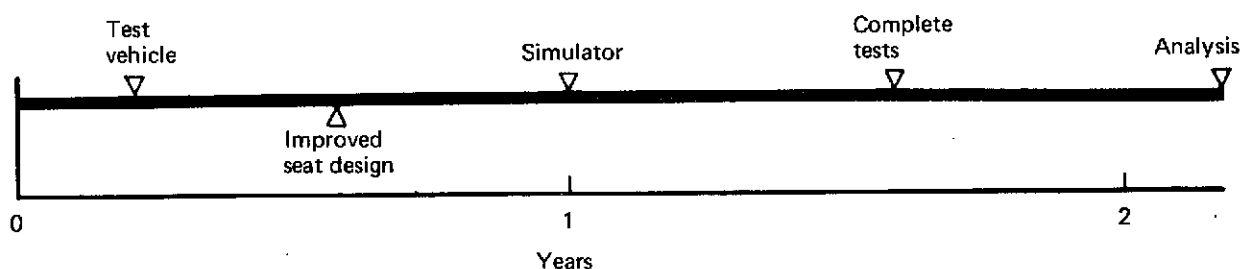
#### WORK STATEMENT

- Design and construct limited-motion simulator
- Design and construct test vehicle
- Develop cues
- Research data on side acceleration passenger tolerance
- Research data on high-speed turnoff for:
  - Airplane
  - Runway
- Develop and qualify passenger seat/restraint system
- Carry out high-speed taxi turnoff tests
- Evaluate and report test results
- Perform tests

#### PAYOFF

- Higher flow capacity
- Less passenger concern

#### SCHEDULE



**FIGURE 65.—PASSENGER TOLERANCE**  
RESEARCH AND TECHNOLOGY SUMMARY

criterion for deciding questions of frequency and schedule. Airlines will take advantage of cooperative ventures that give economic benefits to all, such as the CAB permission to collaborate on reducing frequency on LAX-JFK. The airlines might well be amenable to a fare structure, quota system, or other device that would shift passenger demand away from preferential times and provide airlines freedom of choice in competing for the passenger.

#### 4.2.17.3 Recommended Action

A program would be initiated to investigate, with airline cooperation, passenger preference and passenger request patterns. Analyses would be made to determine what system would shift these patterns. Passenger interviews and questionnaires are recommended. These data would be analyzed to determine what system would shift part of the demand to nonpreferential times.

This system would be developed in conjunction with a study of fees and quotas that would offer incentives to airlines and offer more attractive service at off-peak hours. The objectives of the program would be to develop guidelines for:

- a) More efficient use of airports and airways
- b) Passenger service offering that meets demand
- c) Economical, competitive airline operations.

#### 4.2.17.4 Cost and Schedule

A 7-month program (fig. 66) at a cost of \$50,000 is recommended.

### 4.2.18 Work Package 33—Interior Improvements

#### 4.2.18.1 Potential Payoff

Commercial aircraft interiors have much to do with the airlines' image with the passenger. Clean, comfortable, attractive interiors with easy access and egress are requirements for modern aircraft. Safety features such as emergency evacuation, fire resistance, and smoke exhaust must always be priority requirements. Service items such as galleys, lavatories, and baggage stowage are all important parts of an airline image. Maintaining this interior in a manner that enhances this image is a high-cost item for airlines. Engineering analyses of interior concepts, materials, configurations, and maintenance methods can produce savings in airline maintenance while maintaining or improving standards of safety and esthetics. Any concept that reduced ramp service vehicles would have economic, noise, and emission benefits.

#### 4.2.18.2 State of Readiness

Airlines would be more receptive to any plan that promised to reduce interior maintenance costs. Commercial airlines have used the same interior concept of forward-facing seats with middle aisles ever since the Ford Trimotor was flying. Small departure is made in the lounges of current widebody aircraft. Material technology has advanced rapidly in recent years, including in the areas of durability, stain resistance, fire resistance, and weight. Access and egress is basically unchanged from the earlier commercial aircraft.

#### 4.2.18.3 Recommended Action

- a) Analyze aircraft interior configuration concepts to determine if the standard configuration is optimal. Evaluate concepts on an economic basis.

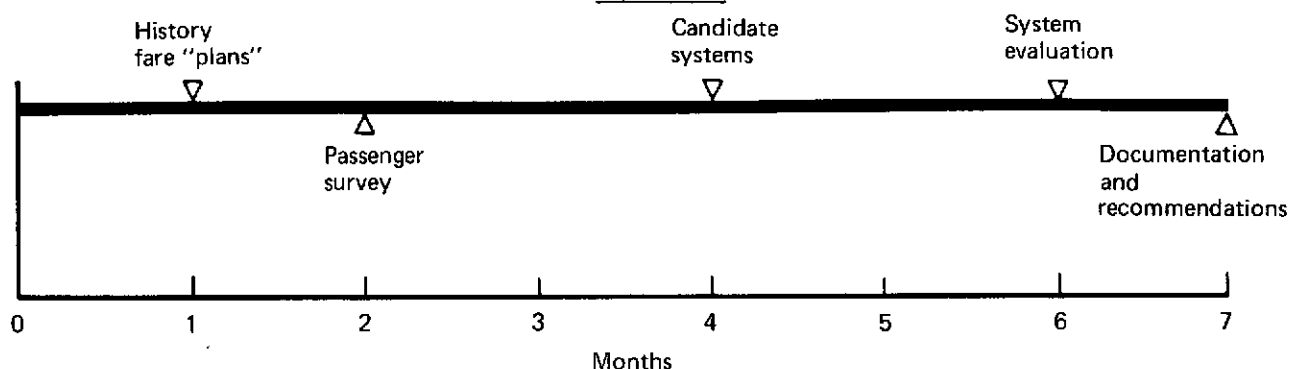
### WORK STATEMENT

- Conduct statistically significant passenger survey to ascertain the flexibility of demand patterns
- Review history of off-peak-hour fare incentive plans including data on the effect of such plans on passenger demand
- Devise systems that would tend to change passenger/airline demand on airport and airway facilities
- Evaluate each system considering:
  - Passenger convenience
  - Airline economics
  - Airport, airway, and ATC efficiency
  - Airline competition both among airlines and with other modes of transportation
- Make recommendations

### PAYOFF

- Equitable plan for spreading schedules
- More effective use of airports and airways
- Better airline economics
- Greater passenger convenience

### SCHEDULE



**FIGURE 66.—SCHEDULE SPREADING INCENTIVES**

#### RESEARCH AND TECHNOLOGY SUMMARY

- Examine possibilities of modular interior concepts for ease of maintenance, including housekeeping. Evaluate on an economic basis.
- Make a study of available materials for all interior components. Determine if material technology advances offer improvements from the standpoint of durability, maintainability, weight, fire resistance, etc.
- Make recommendations for an interior concept mockup and test program.

#### 4.2.18.4 Cost and Schedule

A 6-month program (fig. 67) is recommended costing \$30,000.

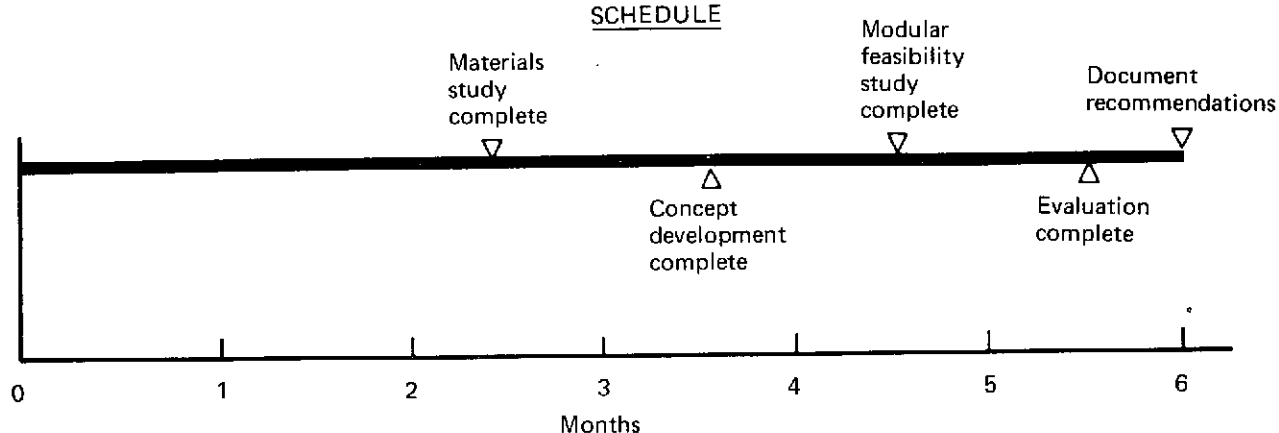
### WORK STATEMENT

- Develop new concepts of aircraft interior configurations
- Examine feasibility of modularization of interiors
- Study state of the art in material technology for possible improved materials for each components of the interior
- Evaluate concepts and/or materials:
  - Economically, including evaluation of aircraft availability due to time saving
  - Esthetically, including passenger comfort
  - Safety
- Recommend feasible concepts for mockup and test

### PAYOFF

- Reduced costs of airline operation
- Better and more comfortable passenger service

### SCHEDULE



**FIGURE 67.—AIRCRAFT INTERIOR IMPROVEMENTS**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.2.19 Work Package 34—Ambient Air Quality Standards Review and Assessment

##### 4.2.19.1 Potential Payoff

The Clean Air Act Amendments of 1970 authorized the establishment of National ambient air quality standards (NAAQS). The NAAQS were published in April 1971 (for CO, HC, NO<sub>x</sub>, particulate matter, SO, and photochemical oxidants), based on reviews of the then-current knowledge concerning these pollutants. At that time, this knowledge was in many respects weak or nonexistent. A number of programs on environmental health have been proceeding since the reevaluation at this time appears appropriate. This assessment of new health and welfare effects information may cause a change in the standards. Research goals may therefore change, and the level of research effort may need to be adjusted accordingly.



#### 4.2.19.2 State of Readiness

The recent energy shortages have raised questions concerning the role of source emission reduction on increased fuel consumption. Are the standards more stringent than required?

The EPA has announced that NO<sub>x</sub> ambient air measurements in the past have been based on a method that has erred on the high side. They are therefore reevaluating the NO<sub>x</sub> emission standards for automobiles. Health effects criteria for NO<sub>x</sub> that were developed in the Chattanooga study are also under review. CO effects are also being questioned. The Russian CO standards, for example, are twice that of the U.S.

#### 4.2.19.3 Recommended Action

Assessment of recent studies of the effects of CO, HC, and NO<sub>x</sub> on plant, animal, and human health is recommended. Results of this assessment should then be evaluated for consideration of possible changes in standards. Phasing the relationship of meteorological pollution precursors to population living habits should be evaluated at different locations for consideration in possible change to the 3-hr CO standard.

#### 4.2.19.4 Cost and Schedule

A \$100,000 effort (fig. 68) for 1 year is recommended.

### 4.2.20 Work Package 35—Terminal Area Air Pollution Model

#### 4.2.20.1 Potential Payoff

In 1970, Congress passed the Clean Air Act, which provided for the establishment of ambient air quality standards that were published in April 1971. The states have attempted to use these standards to measure the amount of emission reduction that should be levied on individual sources. In establishing engine emission standards and goals, the EPA and NASA have used what is technologically reasonable, rather than the requirements to meet the air quality standards of the Clean Air Act, due to the difficulty, without present knowledge, of identifying the specific source causing ambient air quality excesses and levying appropriate emission controls on the source or sources causing this air quality excess (fig. 69).

The advantage of a source identification model approach is that emission control requirements can be based on quantitative rather than judgmental considerations. A more scientifically based

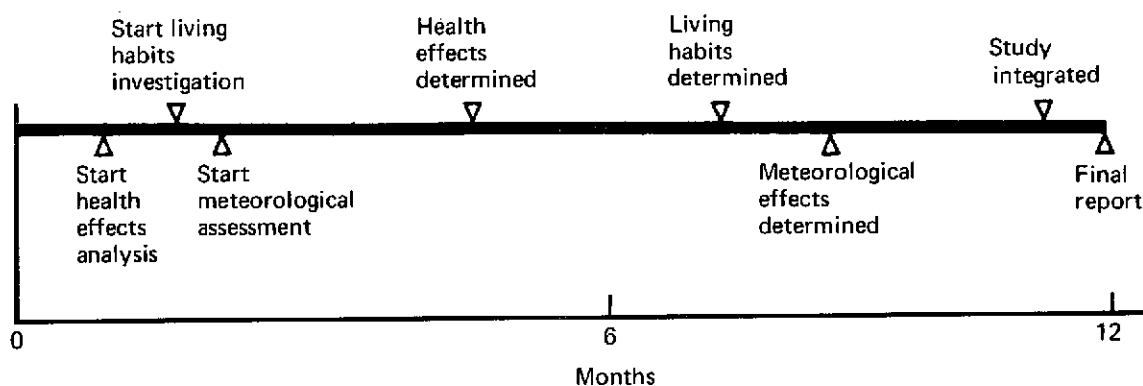
#### WORK STATEMENT

- Assess pollution effects on health
- Assess pollution effects on environment
- Relate pollution exposure to living habits of the population

#### PAYOFF

- Possible change in standards will alter emphasis and level of pollution control effort

#### SCHEDULE



**FIGURE 68.—AMBIENT AIR QUALITY STANDARDS REVIEW AND ASSESSMENT  
RESEARCH AND TECHNOLOGY SUMMARY**

emission control program can then be proposed, giving the desired air quality with minimum economic impact.

#### 4.2.20.2 State of Readiness

Models are used to describe, explain, and predict pollution distribution over a land area. They link pollution concentration at any one point (receptor) to pollution sources (usually at different points). Since pollution moves with the air mass, which is affected by the weather, weather estimates are essential.

Models can be categorized into two classes: those that make a specific prediction of pollution wholly based on mathematical equations for specific sources and weather conditions and those that give probabilities of the occurrence of pollution levels for various conditions of weather and other parameters. These can be called deterministic and probabilistic models, respectively.

In a probabilistic model, recorded air quality concentrations for various meteorological and other variable sets, such as time of day, are tabulated. For example, if measurements of wind speed

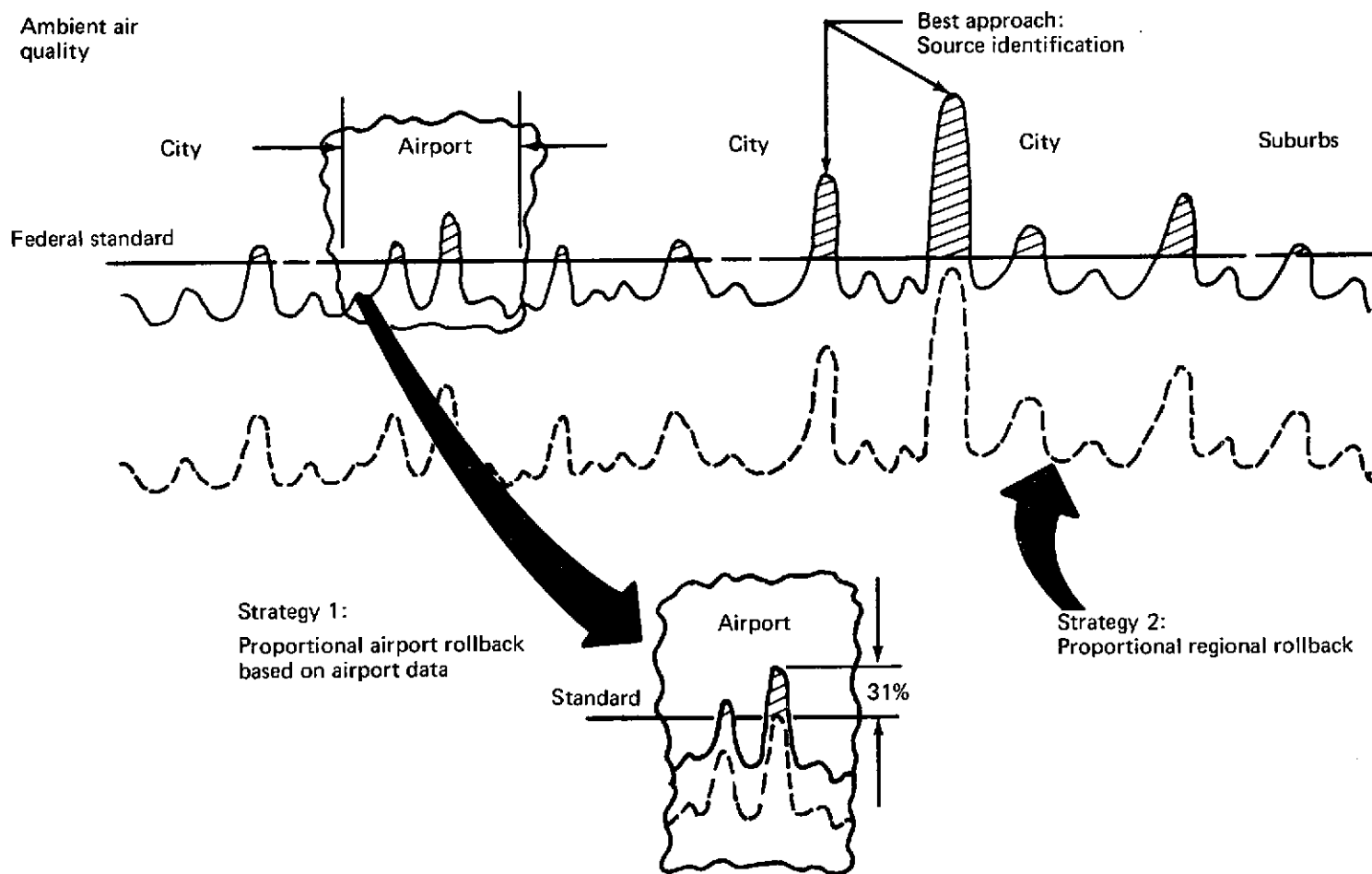


FIGURE 69.—RELATING EMISSIONS TO AIR QUALITY

and inversion height were made simultaneously with air quality concentration on a certain day, it could be assumed that the repetition of these meteorological conditions on some day in the future would result in the same air quality concentration. This would occur only for the same emission pattern. In this scheme, nonlinearly related variables are organized on an empirical basis, thus avoiding a mathematical description that often would be complex in nature.

Deterministic models are those that calculate air quality concentrations at specific receptor locations based on physical characteristics of source emissions and meteorological (dispersion) parameters. An example of this classification is the Gaussian plume dispersion models.

In the Gaussian plume model, the equation relating concentration at the ground along the centerline of the plume to a ground level source emission is expressed as

$$X = \frac{Q}{\pi \sigma_y \sigma_z u}$$

where

X = air quality concentration

Q = source emissions

$\sigma_z$  = standard deviation, vertical direction

$\sigma_y$  = standard deviation, horizontal direction

u = wind velocity

This expression permits concentrations at any distance from a source to be determined. By using hourly average emission and meteorological parameters, air quality for each receptor can be predicted.

A major limitation of models is the poor correlation between calculated air quality values at a particular receptor and air quality measurements taken at the same receptor. This difference is caused by poor measurement procedures taken with unsophisticated equipment, too few measurements to provide good statistical base, and measurements at too few locations to adequately simulate micrometeorological conditions.

#### 4.2.20.3 Recommended Action

There is a need to quantitatively relate emission standards to air quality standards at airport locations. While the many models that relate emissions to air quality are academically precise, they do not correlate well with real-world measurements. A pollution and micrometeorological measurement program at the following airports is recommended:

Los Angeles International  
New York International  
Chicago—O'Hare

San Francisco International  
Atlanta International  
Washington National

Measurements should be taken at and around the airport for particulates, CO, HC, and NO<sub>x</sub>, over a 2-year period. Upon completion of this measurement program, validation of various models can be made.

#### 4.2.20.4 Cost and Schedule

A two-man effort for 3 years is recommended (fig. 70). Air sampling cost for six airports is estimated at \$1.0 million.

### 4.2.21 Work Package 36—Terminal-Area Meteorology Model

#### 4.2.21.1 Potential Payoff

A knowledge of climatological information for airfields permits airplane components to be designed for the expected future conditions that will act on the airplane and be acted upon by the airplane. In this manner, the airplane will not be overdesigned or underdesigned.

#### 4.2.21.2 State of Readiness

Climatological information exists for nearly all major airports, especially within the United States. This is readily available for analysis. Additionally, models of airport wind shear and crosswind and/or tailwind information for the aggregate airport are in existence. Inversion height information is not so readily available, so a greater effort will need to be expended to acquire it.

#### 4.2.21.3 Recommended Action

It is recommended that a two-part program be instituted to acquire the necessary information.

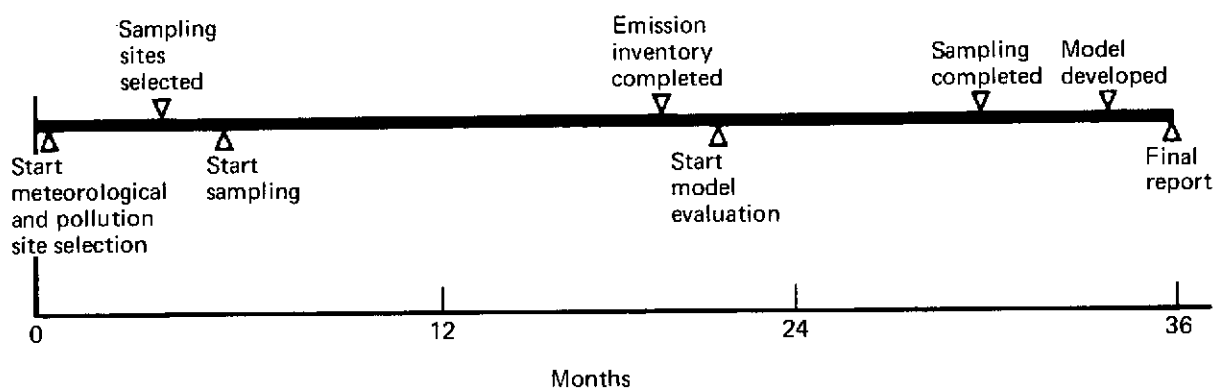
#### WORK STATEMENT

- Select meteorological and pollution sites
- Sample pollutants
- Perform emission inventory
- Develop model
- Validate model

#### PAYOFF

- Emission control requirements tailored to specific ambient air quality requirement schedule

#### SCHEDULE



**FIGURE 70.—TERMINAL AREA AIR POLLUTION MODEL  
RESEARCH AND TECHNOLOGY SUMMARY**

- A short-range effort to develop or obtain the wind shear/tailwind models appropriate to this study
- A literature search and a search of other sources (National Climatic Center, etc.) for inversion height information.

#### 4.2.21.4 Cost and Schedule

A 1 man-year effort over a period of 6 months is recommended (fig. 71) at a cost of \$50,000.

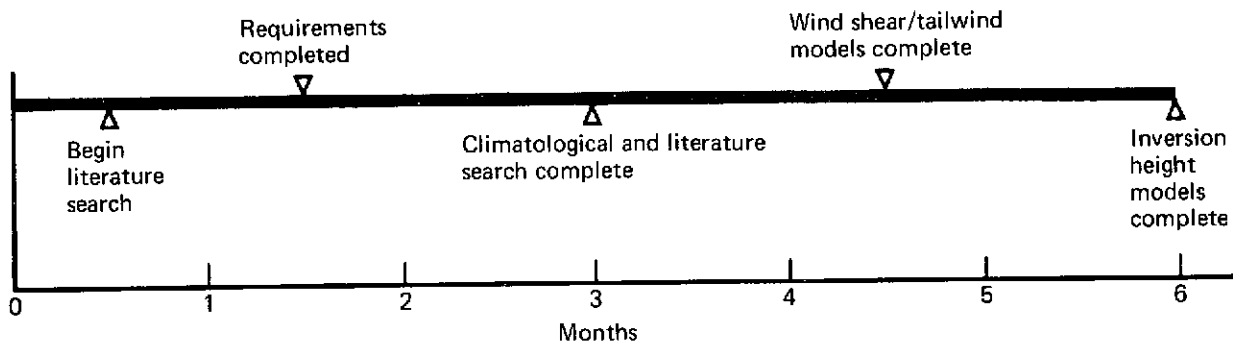
### WORK STATEMENT

- Develop requirements
- Acquire necessary climatological information and institute a literature search
- Develop wind shear/tailwind models
- Develop inversion height models

### PAYOFF

- Realistic and economical airplane design to cope with stated climatological and pollution conditions

### SCHEDULE



**FIGURE 71.—TERMINAL AREA METEOROLOGY MODEL  
RESEARCH AND TECHNOLOGY SUMMARY**

#### **4.2.22 Work Package 37—Pollution-Containment Altitude Determination Based on Actual Inversion Height**

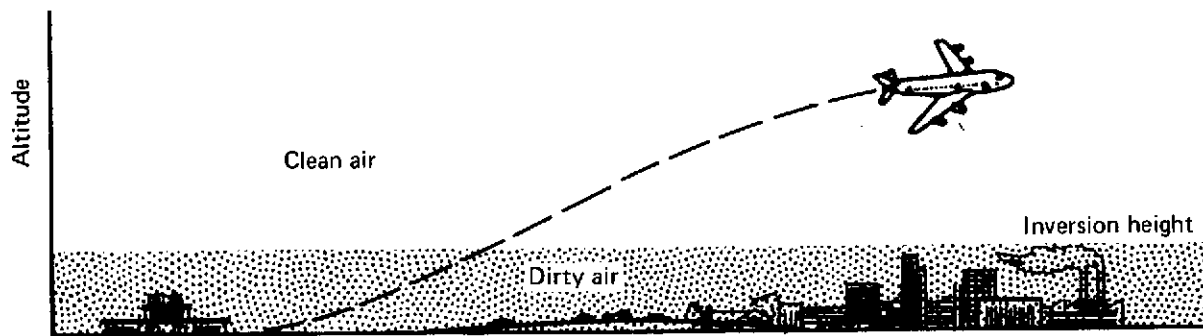
##### **4.2.22.1 Potential Payoff**

The EPA estimates that aircraft pollution around an airport should be contained under a 914-m (3000-ft) height. Average daily inversion heights during high pollution days, however, are significantly lower than 914 m (3000 ft).

It is proposed to use actual daily inversion heights to determine the influence of aircraft emission on the total emissions of the ground area under question. The effect of aircraft emissions on ground air quality can be more realistically determined and emission reductions adjusted accordingly, figure 72.

##### **4.2.22.2 State of Readiness**

Inversion soundings are made daily at numerous locations throughout the United States. Some soundings are taken right at the airport in question (LAX, SLC). Preliminary analysis of average



**FIGURE 72.—IMPACT OF AIRCRAFT EMISSIONS AND INVERSION HEIGHT**

inversion heights at major pollution locations shows inversion heights significantly under 914 m (3000 ft). Preliminary analysis of daily LAX inversions for 1 month show the effective containment altitude to be less than 457 m (1500 ft).

#### 4.2.22.3 Recommended Action

Obtain 2 years of inversion height data at the six major pollution airports. Modify daily inversion of diurnal variations. Determine emissions for the aircraft fleet as each airplane reaches the inversion height for its departure time. Integrate these data into an air quality model for the airport.

#### 4.2.22.4 Cost and Schedule

A 2-man-year effort is recommended, figure 73. Total costs are approximately \$100,000.

### 4.3 RESEARCH AND DEVELOPMENT AFFECTING TAKEOFF OPERATIONS

Noise is the primary concern during takeoff. Means of minimizing takeoff noise are discussed in this section (see fig. 74).

#### 4.3.1 Work Package 38—Reduced-Penalty High-Lift and Low-Noise Concepts

##### 4.3.1.1 Potential Payoff

Development of new design techniques to eliminate costly items for high-lift concepts and to reduce noise for these concepts can result in reduction of the penalty for field lengths reduced to 1524 m (5000 ft) or less from the conventional 2530-m (8300-ft) field lengths (fig. 75). This study



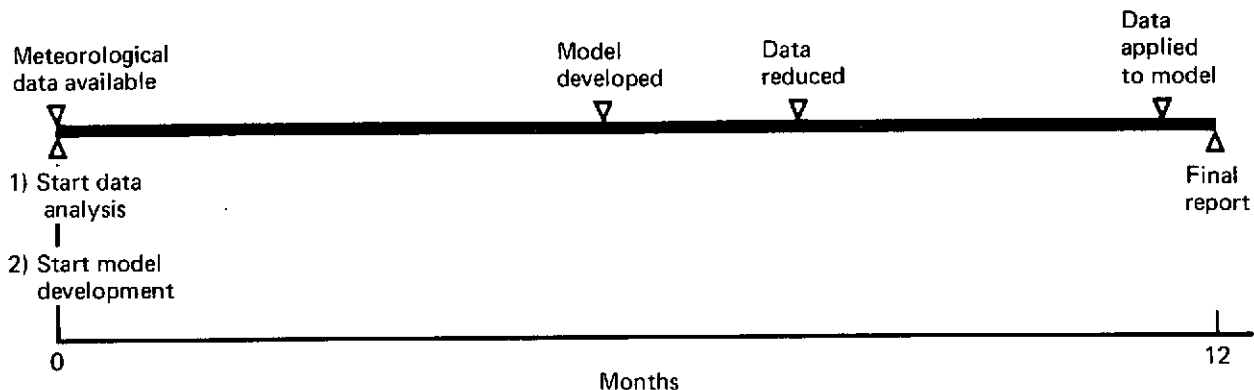
#### WORK STATEMENT

- Obtain meteorological data
- Analyze data
- Develop model
- Apply model to data
- Determine aircraft contribution to pollution

#### PAYOFF

- Credible estimate of aircraft role in pollution
- Emission-reduction requirement can be adjusted accordingly

#### SCHEDULE



*FIGURE 73.—POLLUTION CONTAINMENT ALTITUDE DETERMINATION BASED ON INVERSION HEIGHT*

#### RESEARCH AND TECHNOLOGY SUMMARY

can be extremely important when field lengths below 1524 m (5000 ft) are considered because the penalties are high even without a noise constraint on the sizing of the designs. If the designs are noise constrained, the penalties to economics can be more costly.

#### 4.3.1.2 State of Readiness

High-lift technology research has allowed operation from shorter field lengths. More recently, propulsive lift concepts have been investigated on the AMST and QUESTOL programs. These programs and others currently being undertaken not only evaluate the effectiveness of the high-lift concept, but also must determine the noise associated with each concept. Although these studies allow short-field capabilities, this is at an increasing penalty to DOC as field lengths are reduced. These penalties can be related to the cruise-compromised engine cycle or the low-speed lift-related mechanisms and configuration modifications that are only required for takeoff and landing.

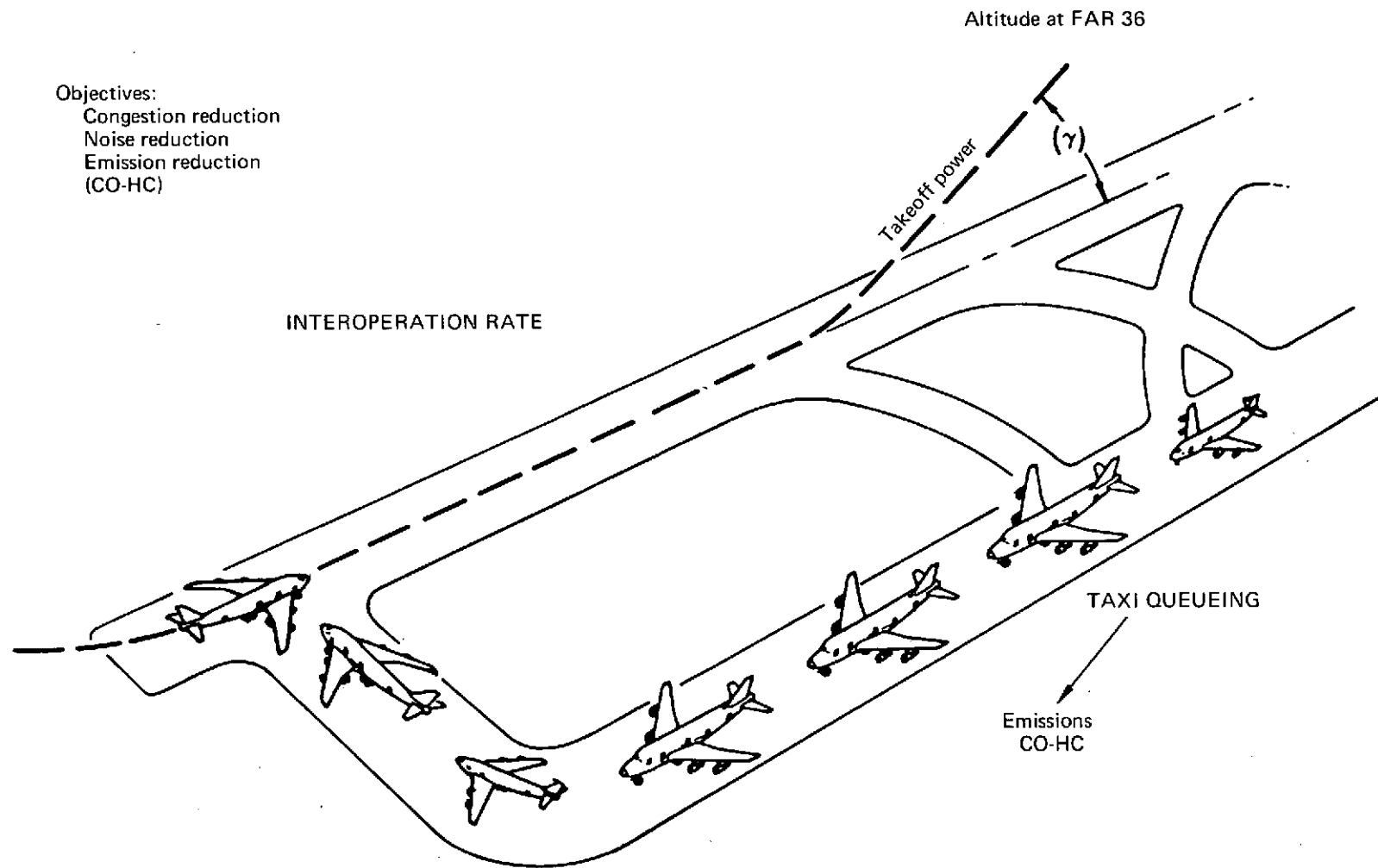
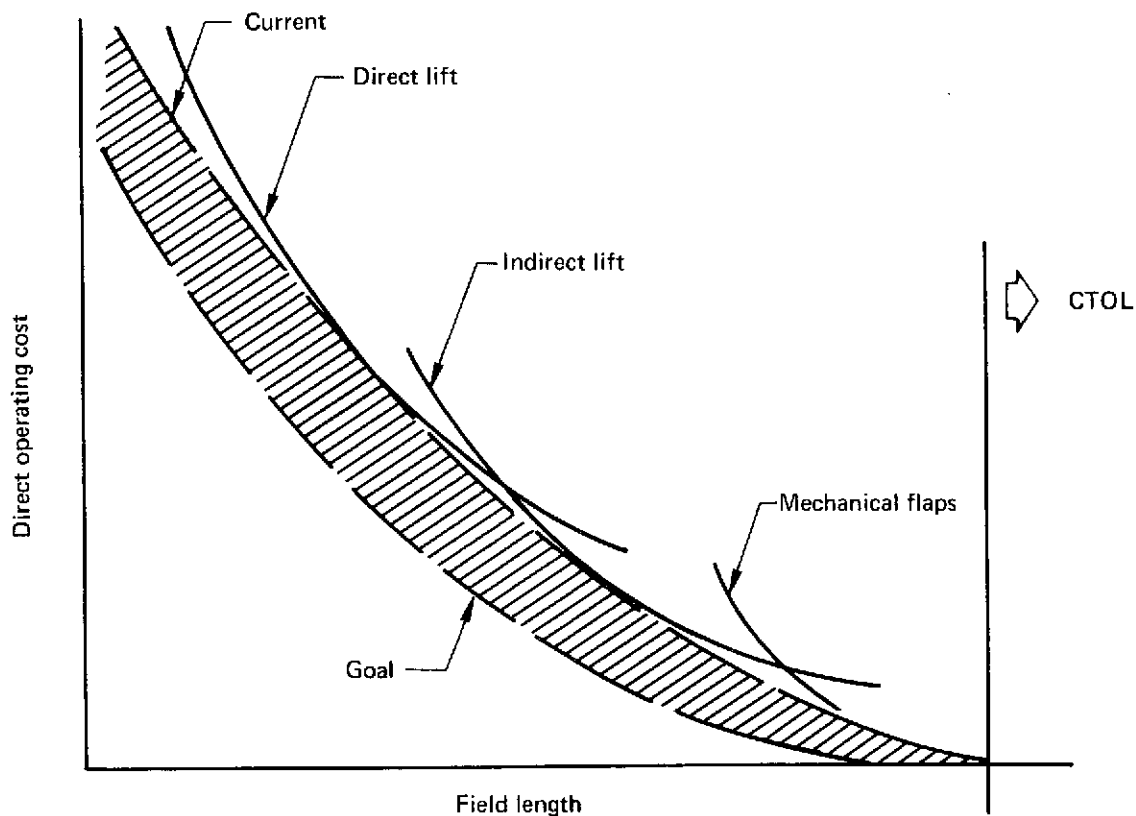


FIGURE 74.—RESEARCH AND TECHNOLOGY AFFECTING TAKEOFF OPERATIONS



**FIGURE 75.—DIRECT OPERATING COST/FIELD LENGTH TRADES**

#### 4.3.1.3 Recommended Action

A program aimed at the design of an RTOL airplane at reduced noise and economics is recommended. The initial work would be to review the current high-lift concepts to isolate the high-penalty items in terms of complexity, weight, and cost and to determine the noise source for each design. Then, new design techniques and new design concepts (overwing engines, etc.) must be devised to eliminate or reduce the impact of these costly items and noise sources.

The next step would be to conduct design studies of competing concepts, possibly at several levels of acoustical treatment to evaluate them on an economic and noise basis. Finally, the most promising concepts would be selected for configuration sensitivity and trade studies and for configuration improvement. These finalized designs would be the basis for economic studies and design definition.

#### 4.3.1.4 Cost and Schedule

The program (fig. 76) would be conducted over a 24-month period at a cost of \$1.2 million.

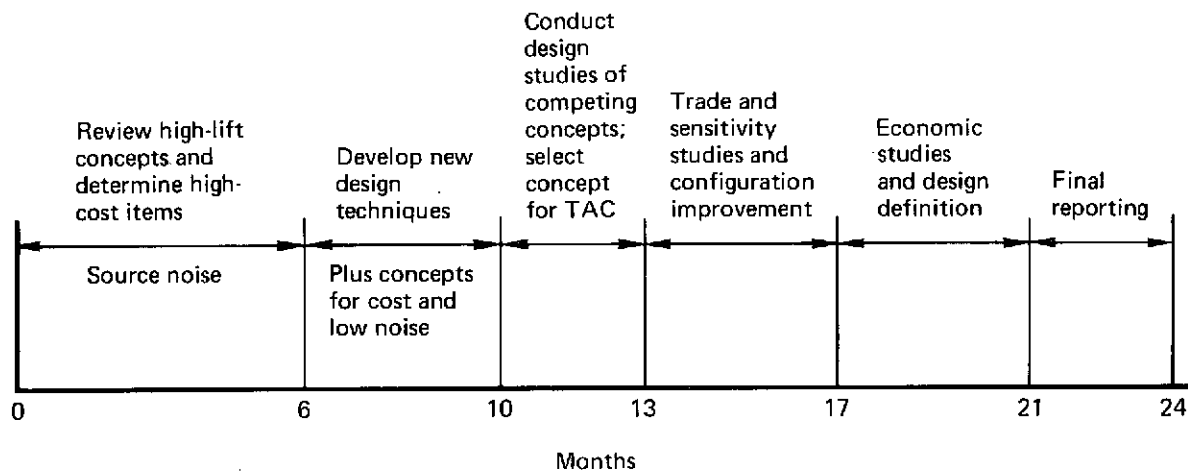
##### WORK STATEMENT

- Review best design to date for each high-lift design concept
- Determine high-cost items of each design
- Develop new design techniques to implement high-lift concept eliminating costly items
- Conduct design studies of competing concepts for economics and noise
- Conduct trade and sensitivity studies

##### PAYOFF

- Reduced cost penalty to achieve reduced field length for takeoff and landing

##### SCHEDULE



*FIGURE 76.—REDUCED-PENALTY, HIGH-LIFT CONCEPTS*

#### 4.3.2 Work Package 39—Advanced, Low-Noise Engine Cycles

##### 4.3.2.1 Potential Payoff

The use of variable geometry to change the engine cycle characteristics has a potential for lowering engine noise levels. Decreases in noise levels may be accomplished without detrimental effects to engine performance.

##### 4.3.2.2 State of Readiness

Present and near-future engines are reaching low-noise goals by the use of acoustically treated inlet rings and duct splitters. These acoustic devices, while providing low noise levels during takeoff

and approach, are also carried on the engine during cruise. This results in large penalties in cruise performance.

Work has been done in generating engines with variable-geometry devices, figure 77, and geared fans, but little has been done to investigate these cycle characteristics in an installed application on an airplane.

#### 4.3.2.3 Recommended Action

The recommended program would include the following tasks:

- a) Generate a parametric engine cycle family that would encompass variable-cycle innovations, including the following:
  - 1) Variable-pitch fans
  - 2) Geared fans
  - 3) Variable-bypass engines
  - 4) Variable turbine geometry
  - 5) Variable exhaust nozzles
- b) Coordinate with the engine manufacturers to evaluate the parametric engine library.
- c) Conduct a study by evaluating the installed effects of the parametric engine library for a conventional airplane application. Trades would be conducted between the various candidate engines with noise and airplane gross weight as the figure of merit.

In addition, using the results of the above study, the potential for developing a candidate engine cycle and performing a flight test evaluation using a 737 aircraft would be considered.

#### 4.3.2.4 Cost and Schedule

The 12-month program plan (fig. 78) would require a total funding of \$150,000.

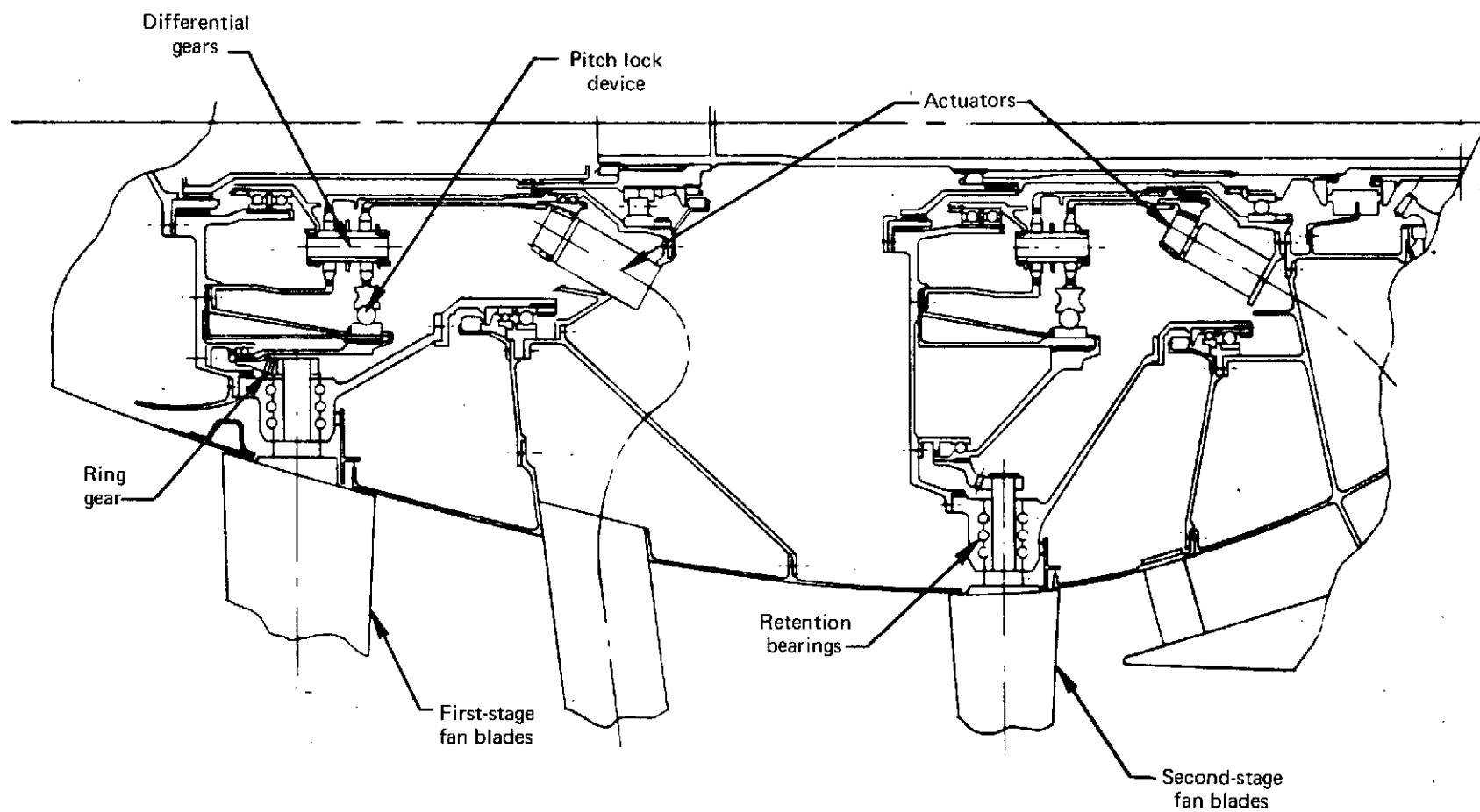


FIGURE 77.—CONCEPTUAL RENDERING OF VARIABLE-PITCH FAN

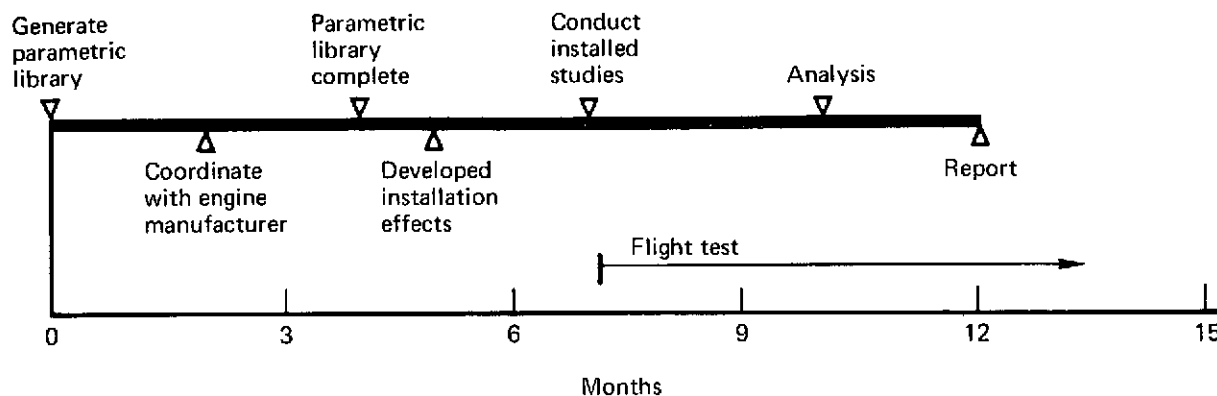
#### WORK STATEMENT

- Generate parametric engine library
- Evaluate parametric engines
- Conduct installed engine study

#### PAYOFF

- Low noise levels with high cruise performance

#### SCHEDULE



**FIGURE 78.—ADVANCED LOW-NOISE ENGINE CYCLES**  
RESEARCH AND TECHNOLOGY SUMMARY

### 4.3.3 Work Package 40—Water Injection Systems

#### 4.3.3.1 Potential Payoff

One method of reducing  $\text{NO}_x$  emissions is to use water injection. Engine manufacturer studies have shown reductions in  $\text{NO}_x$  at takeoff of 80% with water rates of 2% to 3% of combustor airflow.

Present water injection systems are used for thrust augmentation. A system used for control could be operated at constant thrust where significant reductions in turbine inlet temperatures would result. This turbine temperature reduction may have a very beneficial effect on engine life.

#### 4.3.3.2 State of Readiness

Present systems in commercial aircraft use water injection systems for increasing thrust during hot days, for high-altitude takeoffs, and for short runways (see fig. 79). Few airlines actually use

FIGURE 79.—SCHEMATIC OF TYPICAL WATER INJECTION SYSTEM



this system due to problems associated with engine deterioration, system maintenance and reliability, and airline operational procedures.

Because of the tighter pollution controls, a water injection system may be required to control NO<sub>X</sub> emissions for future high-temperature, high-pressure-ratio engines. There has been little done to understand what effect on the engine a water injection system might have when operated at constant thrust. Also, if a water injection system is used more universally for emission control, it may be more efficiently integrated into airline operation with suitable planning.

#### 4.3.3.3 Recommended Action

A multiphase program to develop an efficient water injection system for emission control and to determine the feasibility of this system compared to other emission control systems is recommended.

Phase I would be a coordination effort with airlines and engine manufacturers. Coordination with airlines would be done to fully understand the operational problems associated with a water injection system. Coordination with engine manufacturers would be done to understand exactly what effect water injection has on engine operation.

Phase II would initially develop the ground rules for using water injection to control NO<sub>X</sub> emissions, including the required ambient temperature range. Next, a complete and efficient water injection system would be developed. Included would be the subsystems, including airport storage and transfer systems, heating, and demineralization systems. Also considered would be system components (valves, pumps, etc.) that might tolerate a higher amount of water impurities than do present systems.

Phase III would demonstrate this water injection system using a model terminal facility and determine its feasibility compared to alternate emission control devices. A 737 airplane would be suitable for this work.

#### 4.3.3.4 Cost and Schedule

The 15-month program plan (fig. 80) would require a total funding of \$700,000.

### 4.4 RESEARCH AND DEVELOPMENT AFFECTING CRUISE OPERATIONS

The effect of terminal-compatible features on overall airplane operation are presented in this section.

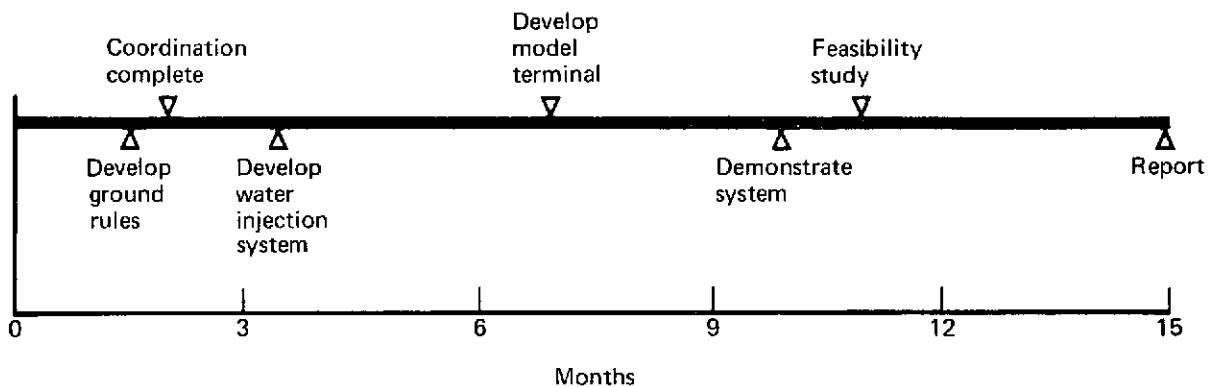
#### WORK STATEMENT

- Coordinate with airlines and engine manufacturers
- Develop ground rules
- Develop efficient water injection system
- Demonstrate techniques with a model terminal facility using a 737 airplane
- Determine feasibility

#### PAYOFF

- Reduced NO<sub>x</sub> emissions
- Possible increased engine life

#### SCHEDULE



**FIGURE 80.—WATER INJECTION SYSTEMS  
RESEARCH AND TECHNOLOGY SUMMARY**

#### **4.4.1 Work Package 41—Low-Cost Inertial Systems**

##### **4.4.1.1 Potential Payoff**

Inertial information is needed for various applications within the avionics and related systems of an airplane, including stability augmentation, dynamic and predictive data for basic displays, navigation, and automatic landing. Since each of these applications has its own requirements on accuracy, dynamic range, and stability, traditional practice has generally been to install separate sensors for each system. With the high redundancy requirements on some of these systems in an advanced airplane, the total number of inertial sensors is large, leading to a compromise between quality of individual units and high total cost.

If sensors of adequate quality for all applications at reasonable cost can be developed and integrated into a central inertial system serving all these functions, considerable total cost savings can be realized while maintaining high effective redundancy and high quality for each application. This would result ultimately in a safer airplane since redundant inertial aiding would now be

available for functions for which high-cost dedicated inertial systems are difficult to justify economically.

#### 4.4.1.2 State of Readiness

One promising approach to low-cost inertial systems is the strapped-down system (fig. 81) in which the complex mechanical platform with its constraints on sensor size is eliminated. Several manufacturers now have rate gyros under development that approach the accuracy and dynamic range requirements of a medium-accuracy strapped-down system. Computers capable of handling the high computation rates required are now available at modest cost. System analysis, gyro error model and improvement, component testing, and system synthesis and testing are needed.

#### 4.4.1.3 Recommended Action

A program involving the assembly and test of several strapped-down inertial systems is recommended, accompanied by extensive error analysis and system application studies. Complete inertial reference and navigation systems using currently available sensors would be designed. The systems would be modeled and the effects of sensor errors determined analytically. Sensors would be tested and modified as needed to meet the system requirements. Assembled systems would be flight tested in various applications, including attitude references, autoland, and combined radio-inertial navigation. The flight tests would be thoroughly instrumented and accompanied by simulation programs to make the best use of the test data in improving sensor and system models.

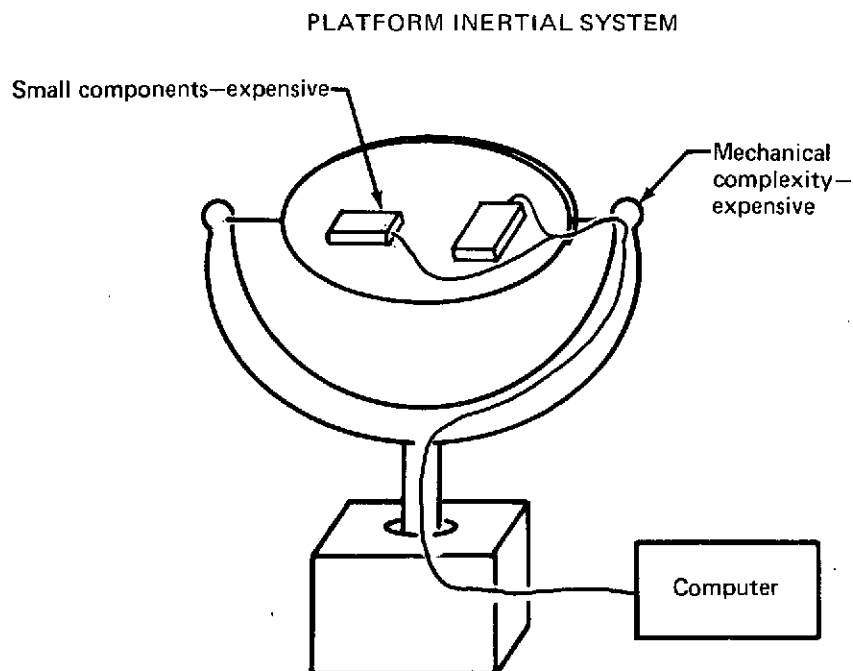
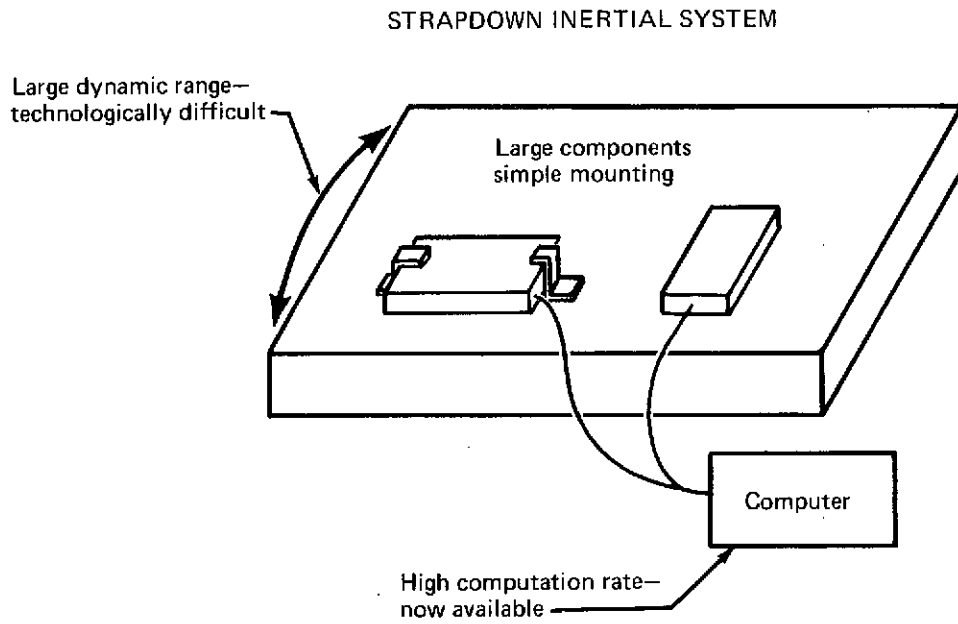
#### 4.4.1.4 Cost and Schedule

The program (fig. 82) would be of 2-1/2-years duration and cost \$1.3 million plus the cost of sensors and the actual flight test costs (these expenses could be shared by manufacturers and other concurrent flight test activities).

### 4.4.2 Work Package 42—VLF Navigation

#### 4.4.2.1 Potential Payoff

VLF navigation systems, such as Omega (fig. 83), have the potential for a continuous-coverage, world-wide, accurate navigation environment at low total system cost due to the small number of ground stations required.



**FIGURE 81.—STRAPDOWN INERTIAL SENSORS—CONCEPTUAL DIAGRAMS**

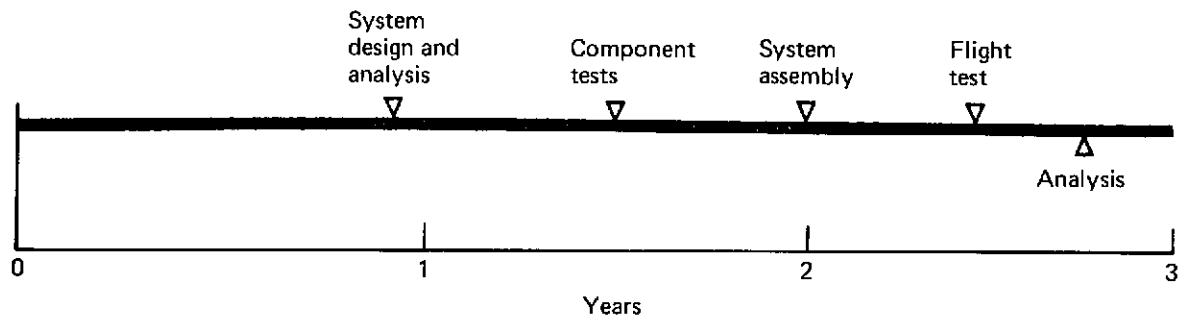
#### WORK STATEMENT

- Design inertial systems
- Analyze systems
- Test and modify components
- Assemble and bench test system
- Flight test
- Analyze tests

#### PAYOFF

- Integrated system would be lower cost system
- Permit inclusion of systems now too costly as separate units
- Greater safety

#### SCHEDULE



**FIGURE 82.—LOW-COST INERTIAL SYSTEMS**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.4.2.2 State of Readiness

The basic Omega transmitting system is being installed by the U.S. Navy and affiliates in other countries. About half the stations are operational now, with the rest scheduled for completion by the late 1970s. A basic accuracy of 1.85 to 3.7 km (1 to 2 miles) has been adequately demonstrated. Theoretical predictions of accuracy on the order of a hundred meters (a few hundred feet) have been made for operation in the differential mode. Limited experiments have not verified this accuracy. Much more information on propagation characteristics as a function of time of day, season, and position is needed before a final estimate of potential accuracy is possible.

Current Omega receivers are too expensive for use by general aviation due to small production runs and lack of an aggressive low-cost design activity. Low-cost VLF navigation receivers (using both Omega and communication transmitters) are inadequate for advanced ATC requirements. Omega cannot replace existing navigational aids until low-cost general aviation equipment is available.

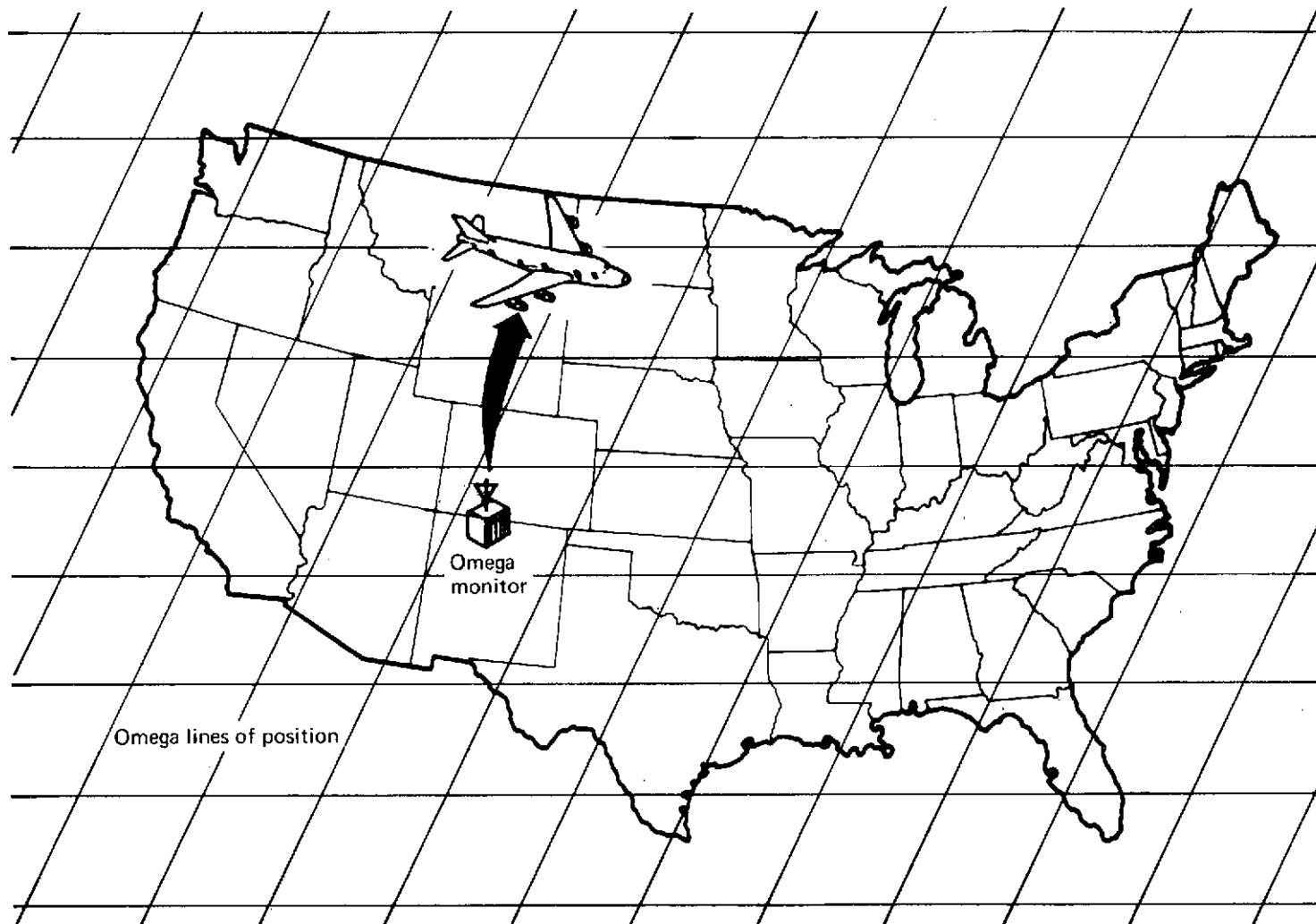


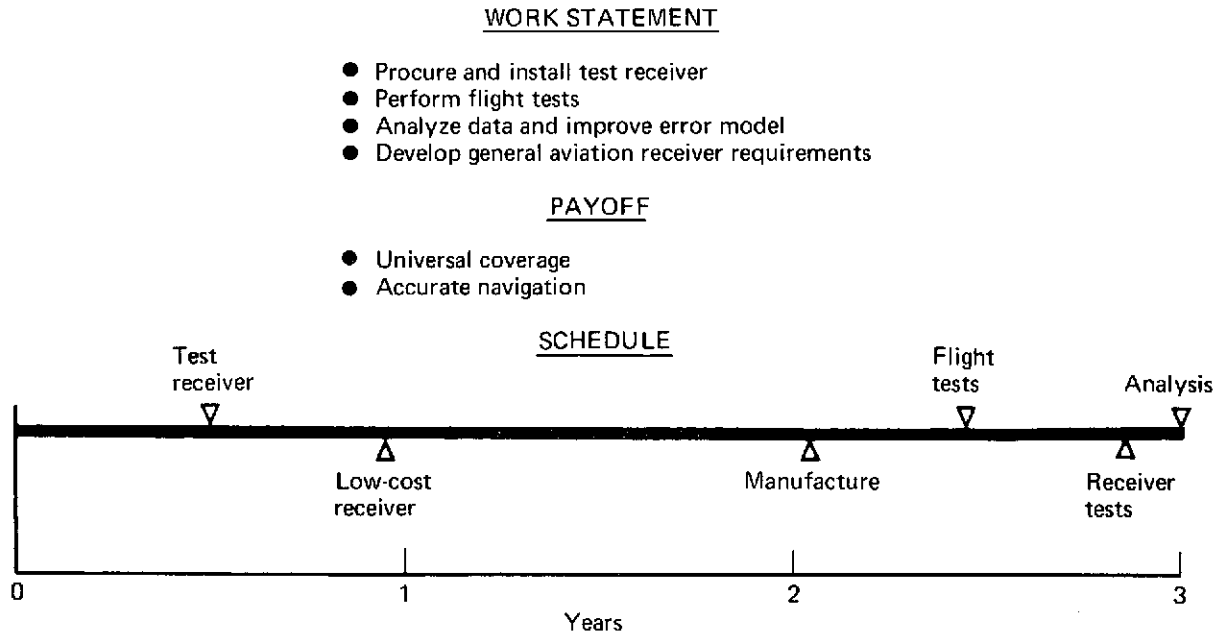
FIGURE 83.—DIFFERENTIAL OMEGA SYSTEM

#### 4.4.2.3 Recommended Action

An extensive propagation measurement program and a low-cost receiver design are recommended. Very high quality receivers would be carried on airplanes that are well-instrumented for recording Omega data and independent position data, such as the NASA RSFS, perhaps in conjunction with other flight tests. Thorough analyses of the data would be used to improve the error model. The program must include operation for all hours of the day and night, all seasons of the year, and a variety of land and sea conditions. Independently, a low-cost receiver suitable for general aviation requirements would be developed.

#### 4.4.2.4 Cost and Schedule

This would be a 3-year program (fig. 84) costing \$900,000.



*FIGURE 84.—VLF NAVIGATION*  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.4.3 Work Package 43—Impact of Cruise Mach Constraint

##### 4.4.3.1 Potential Payoff

The current study of terminal-area compatibility aircraft considered a Mach 0.90 cruise speed. The penalties for terminal-area compatibility may be higher than would have been the case for lower Mach numbers.

#### 4.4.3.2 State of Readiness

The advanced technology required for the Mach 0.90 designs is also applicable to the slower cruise speeds. Aircraft are generally designed to optimize the cruise vehicle with the design compromised to meet landing and takeoff operations. As cruise speeds are reduced, the penalty for low-speed operation becomes increasingly small, and, at the lower speeds, design efficiency increases (see fig. 85).

#### 4.4.3.3 Recommended Action

A program is recommended to determine the TAC penalty associated with airplanes designed to cruise speeds less than Mach 0.90. In the present study, the TAC features were defined and implemented on the Mach 0.90 airplane. These same features would be configured into designs for several cruise speeds less than Mach 0.90. An economic assessment would be made for these airplanes. The high-payoff R&T items identified for the Mach 0.90 airplane also apply to the slower cruise speed airplanes.

#### 4.4.3.4 Cost and Schedule

The program would be a 9-month study (fig. 86) at a cost of \$200,000.

### 4.4.4 Work Package 44—Structural Implications of Outboard Engine Location

#### 4.4.4.1 Potential Payoff

It is expected that a TAC configuration would involve extreme outboard locations for wing-mounted engines to use engine mass flow for inhibition of trailing vortex formation. Few data are available on this type of configuration.

#### 4.4.4.2 State of Readiness

The tools required for a theoretical study are already available. It is thought that the existing aerodynamic theories are adequate, although it would be necessary to confirm this by wind tunnel testing. Experience with airplanes fitted with outboard external stores (B-52) suggests that landing impact loads and flutter are likely to be problem areas.



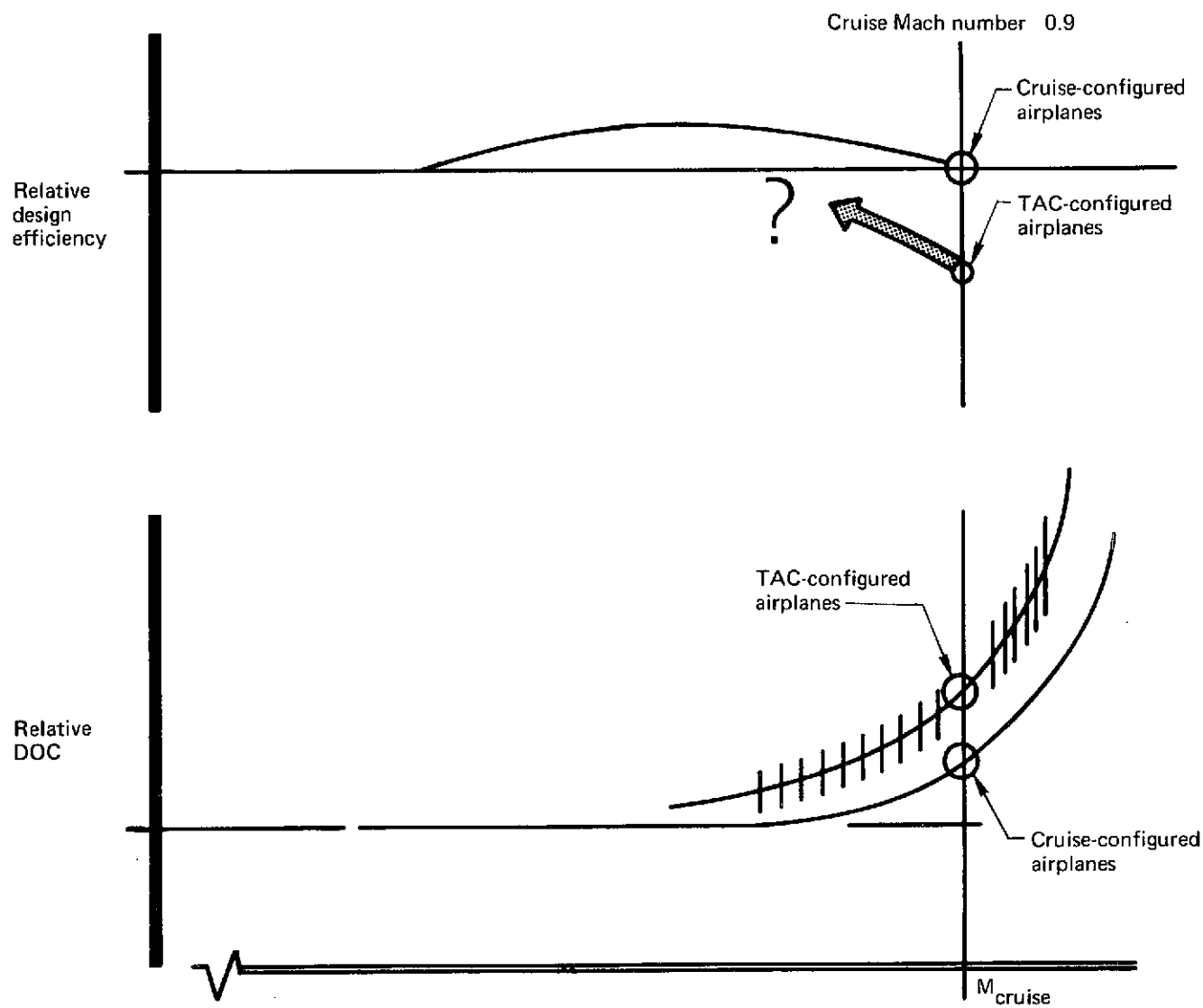


FIGURE 85.—IMPACT OF CRUISE MACH NUMBER CONSTRAINT

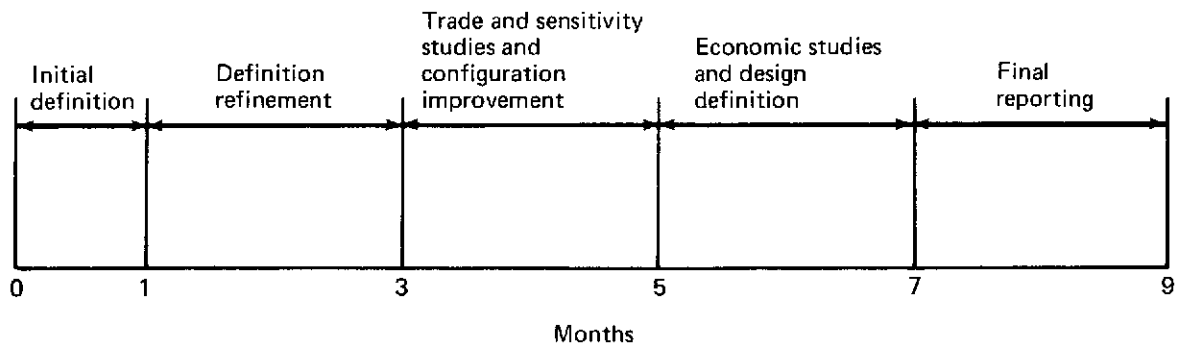
#### WORK STATEMENT

- Investigate airplanes designed to other cruise Mach numbers,  $M_{\text{cruise}} < 0.9$
- Assess economics, fuel use, and noise for each cruise Mach design
- Identify high-payoff R&T areas

#### PAYOFF

- Minimum economic penalties associated with terminal-area compatibility requirements

#### SCHEDULE



**FIGURE 86.—IMPACT OF CRUISE MACH CONSTRAINT**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.4.4.3 Recommended Action

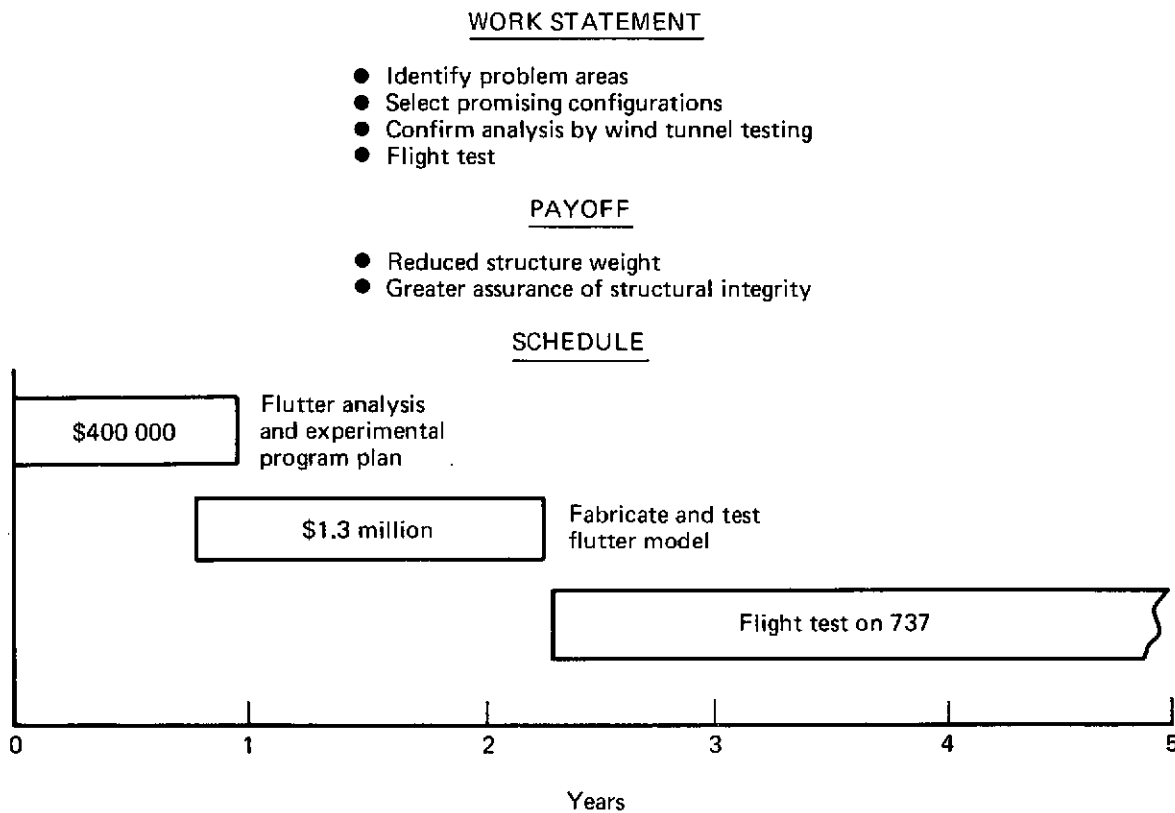
A theoretical study is recommended in which configurations would be considered covering a wide range of parameters such as aspect ratio, taper ratio, sweep angle, and engine location. Each configuration would be analyzed from the viewpoint of static and dynamic loads, stress, and flutter. In addition, sensitivity studies would be carried out to determine the sensitivity of the analyses to such things as cowl aerodynamics. As a result of these studies, problem areas and the more promising configurations would be identified.

A program of dynamic low-speed wind tunnel testing is recommended to validate the analyses. These could probably be done by modifying existing models, thus saving time and cost.

Depending upon the feasibility of mounting an outboard engine (real or dummy) on a flying test bed, a flight test program following a ground vibration test would be desirable to further validate the analysis in the areas of flutter and dynamic loads.

#### 4.4.4.4 Cost and Schedule

Phases I and II are expected to be a 27-month program costing \$1.7 million. The follow-on flight test program is a 30-month program with no cost estimate being made at this time (see fig. 87).



**FIGURE 87.—STRUCTURAL IMPLICATIONS OF HIGH-ASPECT-RATIO WING**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.4.5 Work Package 45—Outboard Engine Mounting on High-Aspect-Ratio Wings

##### 4.4.5.1 Potential Payoff

High-aspect-ratio wings can improve low-speed aerodynamic performance and have a favorable effect on takeoff noise. Mounting engines outboard on these wings can aid in dissipating wingtip vortices, thus allowing closer spacing of aircraft during takeoff and landing. Engine strut and mount material selection and detail design can be made to ease the problem of tuning the structural frequency to avoid wing flutter penalties.

#### 4.4.5.2 State of Readiness

The outboard strut for the 747 airplane was “tuned” to minimize wing flutter penalties, and strut tuning has been studied on the B-52. The TAC configuration is unique in that the engine is relatively larger and further outboard on a smaller cross section wing than was the case on the 747 and B-52.

#### 4.4.5.3 Recommended Action

It is recommended that engine/wing configurations be studied and developed to determine the practicality of installing large engines in small wing cross sections with engine struts “tuned” to desired natural structural frequencies. Alternate engine positions and load paths should be analyzed to determine the range of natural frequencies available. The emphasis in this study would be to develop practical detailed structural arrangements to yield an engine strut design compatible with minimum-weight wing structure.

#### 4.4.5.4 Cost and Schedule

This 6-month study (fig. 88) is estimated to cost \$100,000.

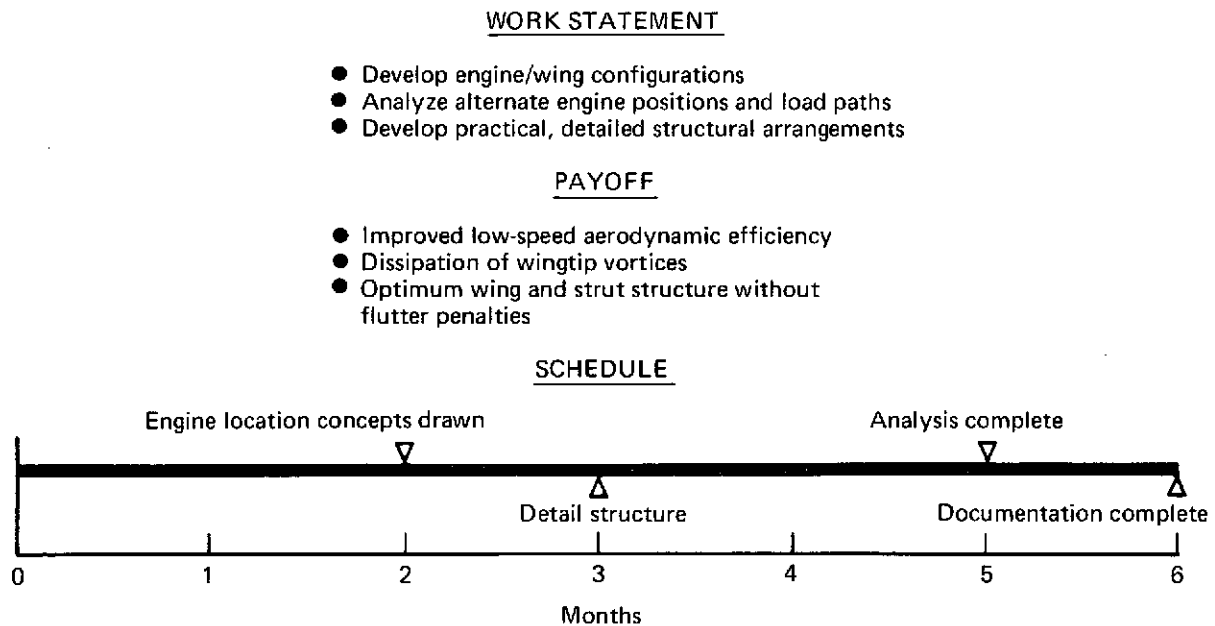


FIGURE 88.—OUTBOARD ENGINE MOUNTING ON HIGH-ASPECT-RATIO WINGS

RESEARCH AND TECHNOLOGY SUMMARY

#### **4.4.6 Work Package 46—Guidance and Control Integration**

##### **4.4.6.1 Potential Payoff**

Extensive capabilities are required of the guidance and control systems of advanced airplanes. Many of the functions must be triple or quadruple redundant (fig. 89) for safety. The total cost can be kept from becoming excessive by combining like functions as far as practical without compromising safety.

##### **4.4.6.2 State of Readiness**

Most of the elements of an integrated G&C system are available now. No experience with such complete systems, operating under realistic conditions, has been acquired yet. Airline acceptance is dependent on well-proven capability and low cost of operation. The NASA RSFS has much of this equipment installed and will begin its flight tests by evaluation of its operation.

##### **4.4.6.3 Recommended Action**

An extensive flight test and demonstration of an integrated guidance and control system on a commercial-type airplane is recommended. The assembled system would consist of hardware as much like eventual operational equipment as is consistent with the flexibility required in a flight test program. The electrical, functional, and operational interface with PWI/CAS systems, weather radar, landing monitor, data link, MLS, and the ATC/RNAV system would be studied. Operational procedures, man/machine interaction, reversion modes, and maintenance problems would be emphasized. Thorough instrumentation is essential.

##### **4.4.6.4 Cost and Schedule**

This would be a 3-year program (fig. 90) costing \$2 million.

#### **4.4.7 Work Package 47—Secondary Power System Redundancy**

##### **4.4.7.1 Potential Payoff**

On advanced airplanes where operational advantages of various sorts are achieved by increased reliance on electrical, electronic, hydraulic, and pneumatic systems (autoland, neutral stability, LAMS), the secondary power system must be highly redundant (fig. 91). Meeting this requirement can incur a considerable weight and cost penalty. To minimize this penalty, components and system configurations giving maximum effective redundancy at minimum cost and weight are needed.

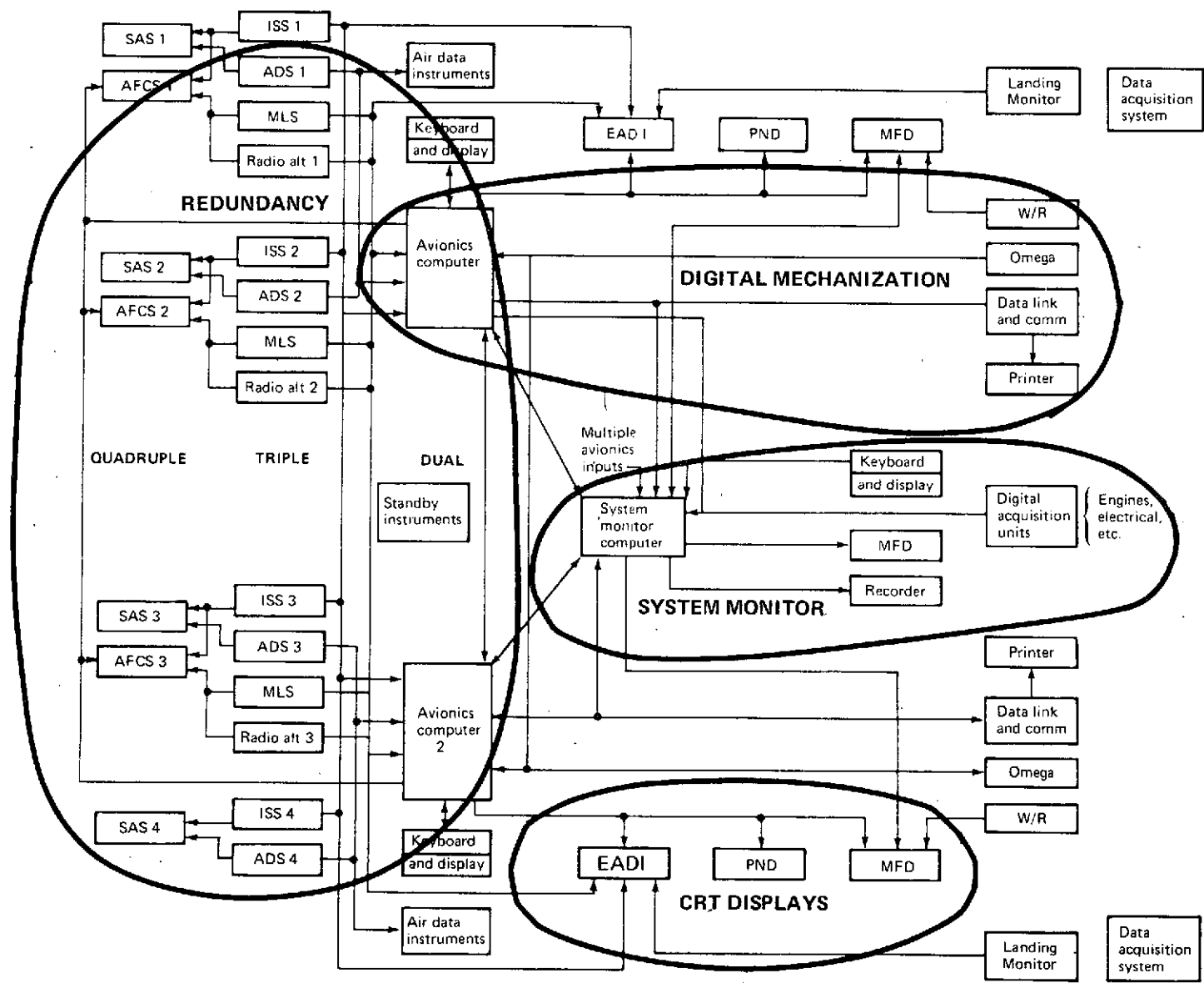


FIGURE 89.—INTEGRATED GUIDANCE AND CONTROL SYSTEM

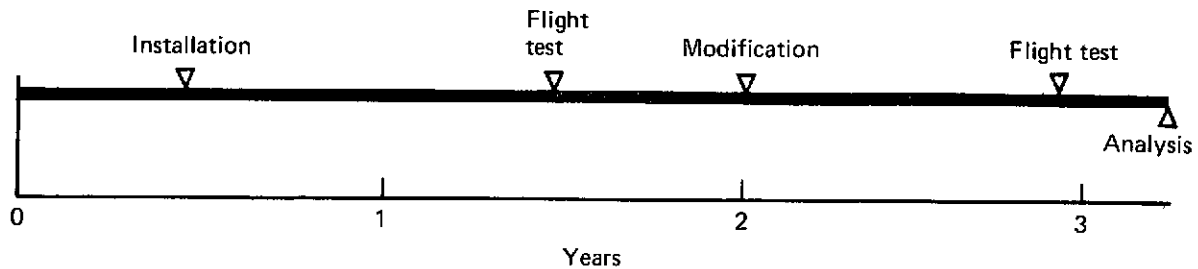
#### WORK STATEMENT

- Assemble system
- Flight test

#### PAYOFF

- Low cost
- Accurate guidance
- Greater safety

#### SCHEDULE



**FIGURE 90.—GUIDANCE AND CONTROL INTEGRATION  
RESEARCH AND TECHNOLOGY SUMMARY**

#### 4.4.7.2 State of Readiness

The secondary power systems for large commercial jet transports are normally tailormade to the requirements of each specific airplane model. The power source and user systems (hydraulic, pneumatic, and electrical) are treated as individual systems each with a required degree of redundancy. These levels of redundancy are normally based on historical component failure data of critical components and safety criteria requiring safe operation of the airplane after a given number of system failures. Improvements in critical components and integration of the power sources could result in appreciable weight savings (e.g., elimination of components such as redundant hydraulic pumps and associated plumbing).

It should be noted that part of the secondary power system will always be configuration critical.

#### 4.4.7.3 Recommended Action

It is recommended that background data and elements that make design for redundancy easier be developed. This development should be conducted during phase I; key elements will be identified for development (more reliable, lighter, more capable), and general models and principles of redundant design will be developed. Phase II is the development of hardware items identified in phase I. The intent would be to develop these items and concepts to a level that would allow them to be experimentally flight tested in a suitable airplane.

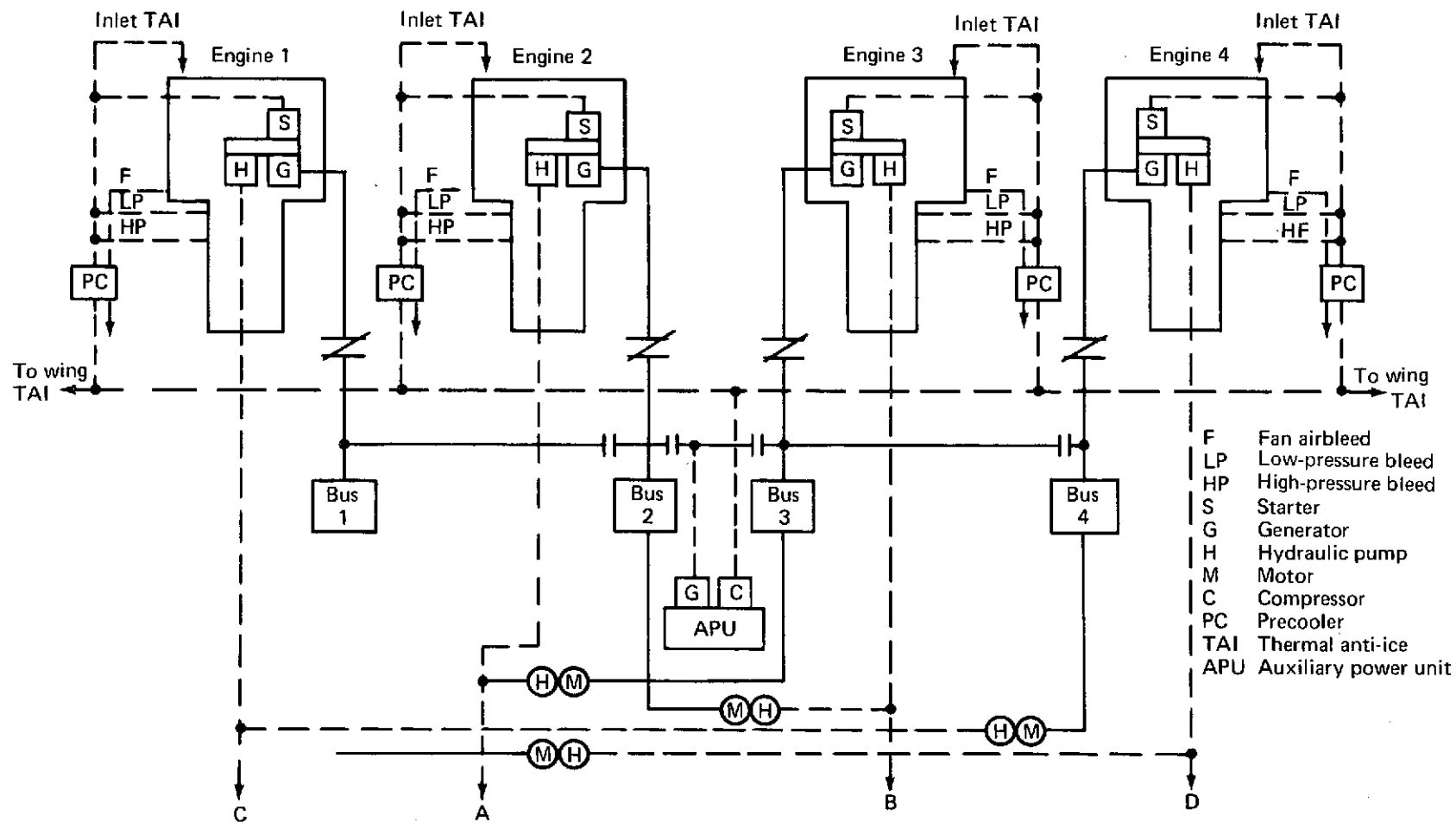


FIGURE 91.—TYPICAL REDUNDANT SECONDARY POWER SYSTEM



#### 4.4.7.4 Cost and Schedule

The program (fig. 92) would require up to 3 years. Phase I would take up to 1 year and is estimated to require a total funding of \$100,000. Phase II would follow phase I. The cost of phase II would depend upon the recommendations made at the conclusion of phase I.

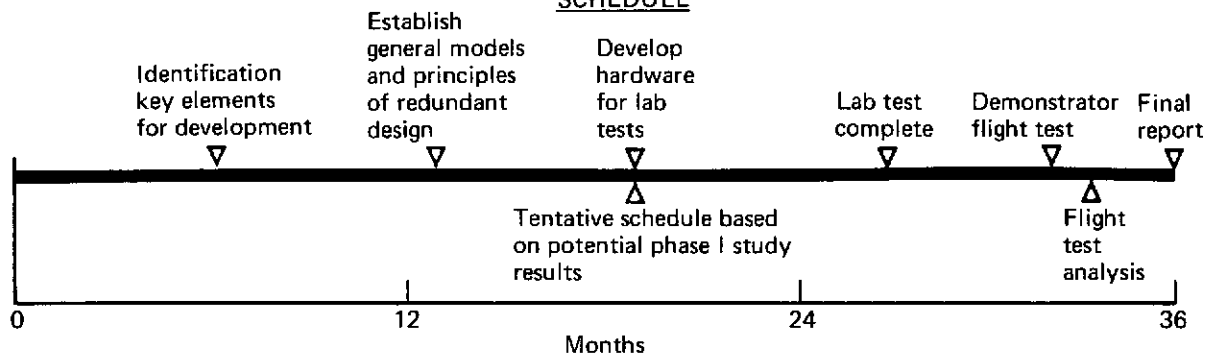
##### WORK STATEMENT

- Phase I
  - Identify key elements
  - Develop general models analytically
  - Develop principles of redundant design
- Phase II
  - Develop and test identified hardware
  - Evaluate flight test

##### PAYOFF

- Operational advantages achieved with potential weight reduction

##### SCHEDULE



**FIGURE 92.—SECONDARY POWER SYSTEM REDUNDANCY  
RESEARCH AND TECHNOLOGY SUMMARY**

#### 4.4.8 Work Package 48—Airplane Design/Energy Relationships

##### 4.4.8.1 Potential Payoff

Designers of future aircraft are faced with the situation that the 25-year lifetime of an advanced, next-generation aircraft may coincide with geological history during which half of the earth's recoverable oil (90% of U.S. oil), which all current aircraft depend upon, will be consumed. Substantial pressures will exist for various fuel conservation measures. Furthermore, there is the possibility of escalation of JP fuel prices beyond "normal" inflation and supply-demand influences due to pressures from foreign oil suppliers. They furnish 35% of today's U.S. oil use and will likely supply 40% to 50% by 1975.

These circumstances make it prudent for those concerned with advanced aircraft planning to review current design procedures in light of the uncertain fuel environment. The payoff for this effort will be savings, not yet amenable to estimate, in national fossil fuel energy resources.

#### 4.4.8.2 State of Readiness

Some studies have been made of current aircraft to establish fuel-optimized flightpaths. Fuel savings have been identified and these energy conservation measures have been put into practice at some of the nations major airlines.

Other preliminary studies have considered advanced aircraft design in terms of energy conservation. Many of these have, however, considered advanced fuel concepts such as liquid hydrogen or other hydrogen-based fuels. A recent symposium, hosted by the NASA Langley facility, "Working Symposium on Liquid-Hydrogen-Fueled Aircraft," summarized the status of work accomplished in this field.

Since many of these advanced fuel concepts require substantial reorientation of the entire national fuel recovery and distribution system, it may be several decades before a commercial fleet of such advanced fuel aircraft can be realized. In this case, it becomes prudent to assess in what ways aircraft using conventional fuel can be modified to provide more efficient productivity per unit energy expended.

Another aspect of energy conservation concerns its relationship to the environment. The typical conflict between the energy benefits of coal and its degradation of the land by open-pit mining or degradation of the air by high sulfur content is well known. What may be less clear is a similar conflict that occurs in aircraft design. Figure 93 illustrates the impact on block fuel for a typical 200-passenger, long-range commercial transport of increasingly severe noise restrictions. This study has given preliminary indications of other interaction between aircraft energy use and the noise, congestion, and pollutant aspects of aircraft design.

The above studies can and should be expanded to explore all opportunities for increased passenger distance per amount of fuel for advanced aircraft design.

#### 4.4.8.3 Recommended Action

A comprehensive preliminary design effort is recommended which would explore energy-conserving design opportunities for typical advanced commercial transports. The principal study output would be identification of critical research and technology areas.

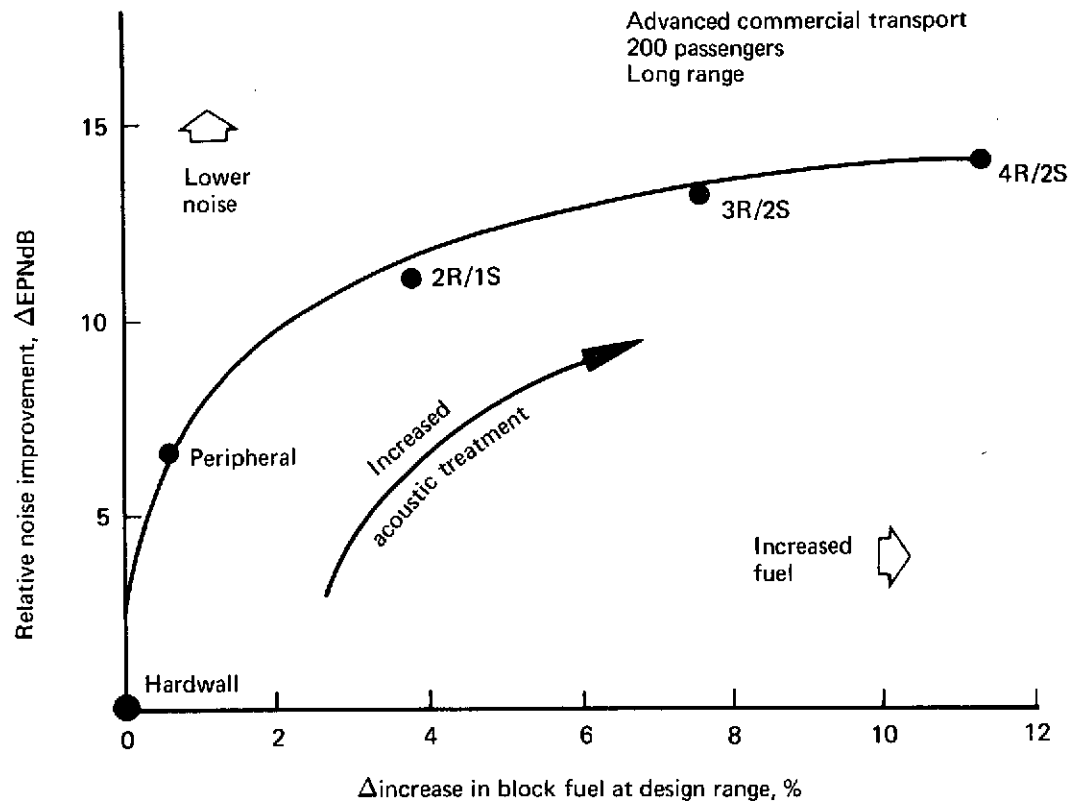


FIGURE 93.—ENERGY IMPLICATIONS OF NOISE REDUCTION

An initial assessment would be made to understand the overall energy flow of the various aspects of aircraft operation. This would include energy expended in manufacturing as well as in service. This information is required to enable the designer to understand the trades between: fuel use and structural weight, manufacturing complexity and cruise performance, and others. Data would also be assembled concerning projected supplies and prices of conventional aircraft fuel.

Next, potential design parameters judged to have significant impact on either manufacturing or operational energy use would be identified. These would include but not be limited to: cruise Mach numbers, wing planform parameters (sweep, aspect ratio, thickness, etc.), engine type and cycle, structural design, and others.

Each of the design changes would be parametrically incorporated into a baseline airplane and the effect on overall energy use would be studied. Simultaneously, advanced configuration concepts that could provide structural efficiency or payload efficiency improvements would be assessed.

The preliminary studies would be used to conceive and configure an "energy conservation" airplane. The overall performance of this airplane would be determined and an economic assessment made in terms of today's and future fuel costs. The potential saving of energy would be defined.

As a result of these studies, significant research and technology areas would be identified and recommendations made concerning the direction of future efforts toward cost-effective goals.

#### 4.4.8.4 Cost and Schedule

A 12-month preliminary design effort (fig. 94) costing approximately \$300,000 is judged to be required to complete the above work items.

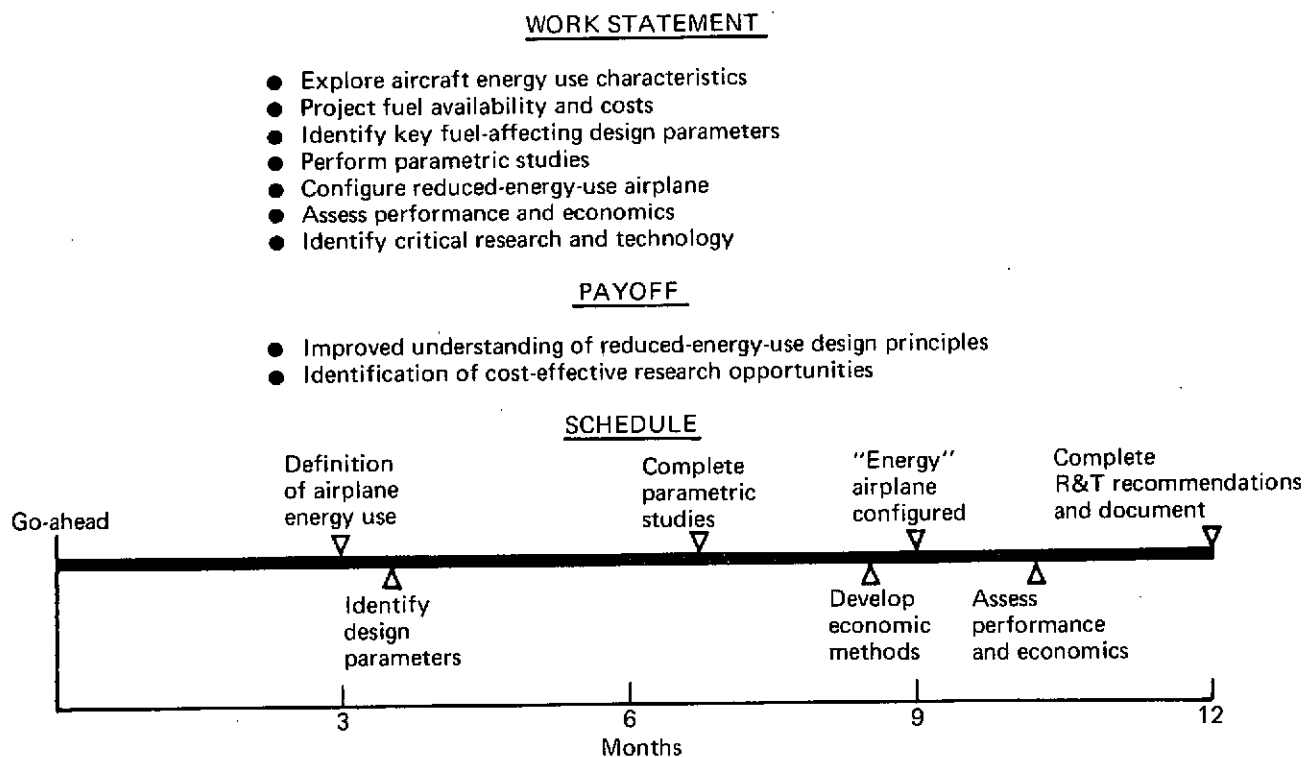


FIGURE 94.—AIRPLANE DESIGN/ENERGY RELATIONSHIPS  
RESEARCH AND TECHNOLOGY SUMMARY

#### **4.4.9 Work Package 49—Innovative Airplane Concepts for TAC Application**

##### **4.4.9.1 Potential Payoff**

With the projected increase in traffic forecast for the future, congestion, emissions, and noise goals will become increasingly difficult to meet. One solution lies in designing larger, more efficient airplanes such that fewer airplanes would be required.

##### **4.4.9.2 State of Readiness**

Increasing the size of conventionally configured airplanes would help to relieve the congestion problem. However, airplanes larger than the current 747 tend to be less efficient in terms of productivity due to the square-cube effect on weights. New innovative designs could lead to an improvement in efficiency while improving TAC (see fig. 95). An example of innovative designs would be the use of the distributed load concept.

##### **4.4.9.3 Recommended Action**

A program is recommended leading to design of a large-payload TAC airplane having less noise and emissions relative to conventional designs carrying the same payload. The initial phase would be to study innovative large airplane concepts such as flying wings and tandem wings with the objective of identifying design features for high payload/TOGW keeping in mind terminal-area compatibility. Then, design studies using the competing concepts will be conducted. Of these designs, the most promising concept will be selected for more detailed design studies. The “high payoff” research areas required for this design will be identified.

##### **4.4.9.4 Cost and Schedule**

The program would be scheduled over a 15-month time period (fig. 96) at a cost of \$350,000.

#### **4.4.10 Work Package 50—Advanced Fuel Airplane Concept**

##### **4.4.10.1 Potential Payoff**

Atmospheric pollution and hydrocarbon fuel availability projections dictate the need for a new aircraft fuel in the future. Liquid hydrogen as a fuel offers a potential for meeting both the pollution and availability requirements.

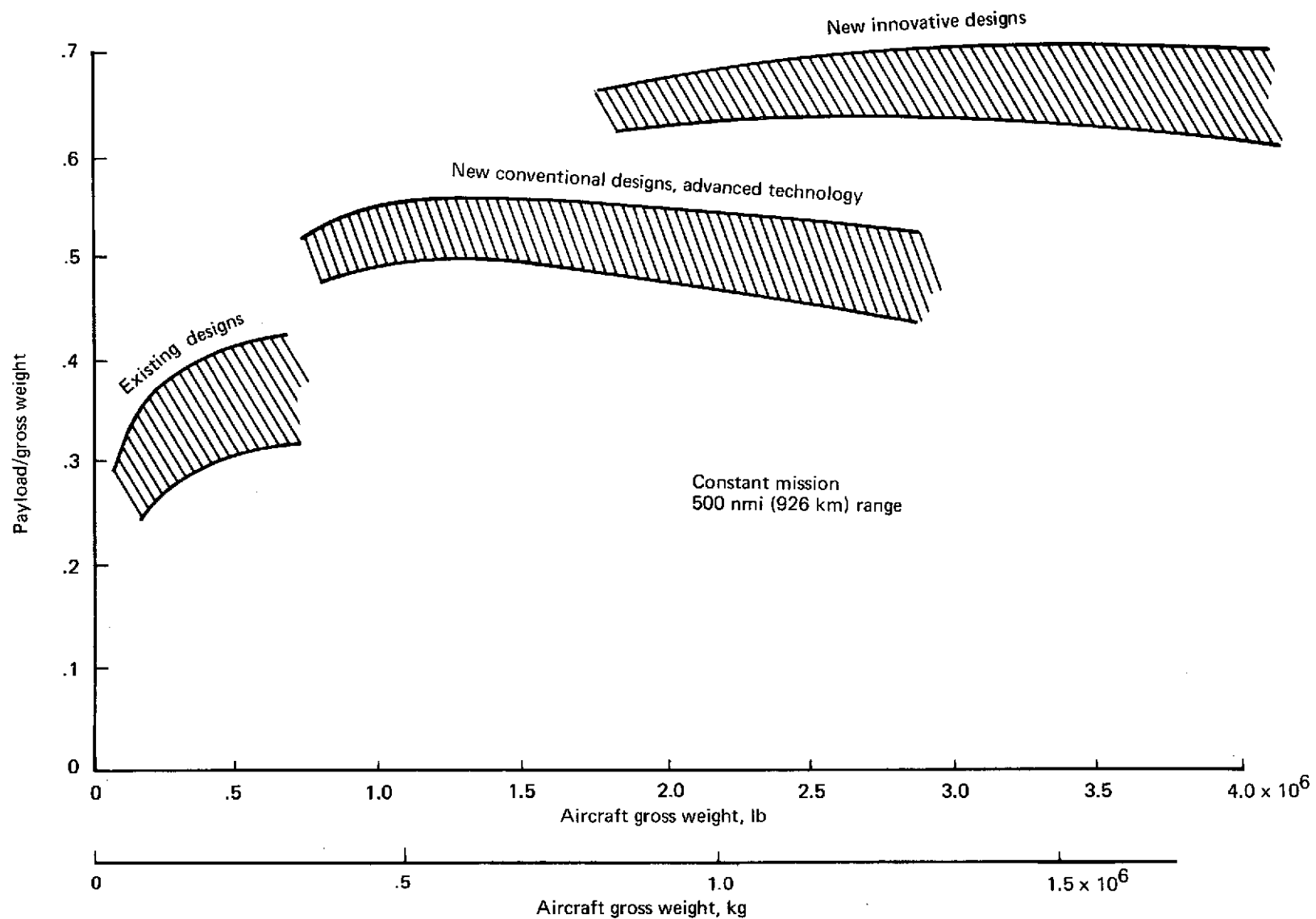


FIGURE 95.—INNOVATIVE PAYLOAD/GROSS WEIGHT DESIGNS

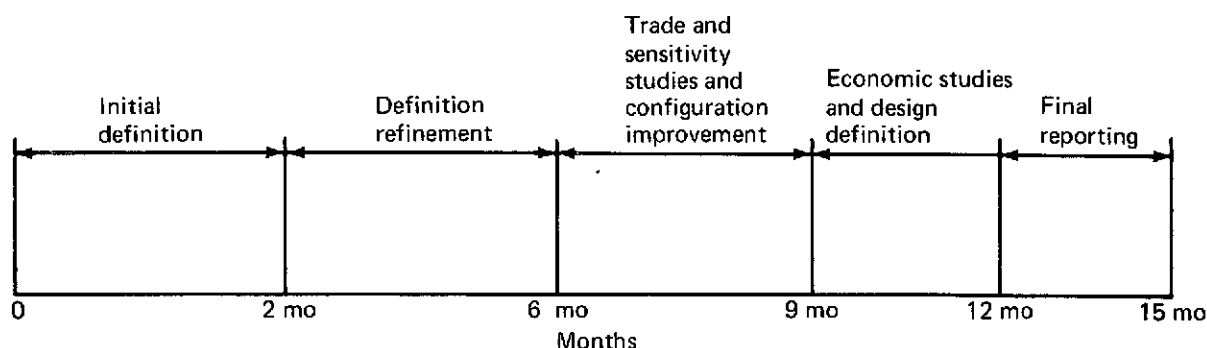
#### WORK STATEMENT

- Study large-airplane concepts such as flying-wing and tandem-wing airplanes
- Identify design features for high-payload/TOGW, together with terminal-area compatibility
- Conduct design studies of competing concepts
- Select most promising concepts for more detailed design studies
- Identify the high-payoff R&T areas

#### PAYOFF

- Reduced congestion, emissions, and noise while retaining competitive economics

#### SCHEDULE



**FIGURE 96.—INNOVATIVE AIRPLANE CONCEPTS FOR TAC APPLICATIONS**  
RESEARCH AND TECHNOLOGY SUMMARY

#### 4.4.10.2 State of Readiness

The development of hydrogen as a fuel has been in progress since 1957. The primary use has been for the upper stages of space vehicles such as the Saturn S-II and S-IVB. A large selection of flight-weight components, such as valves, joints and pumps, have been developed and proven in use for both liquid and gaseous hydrogen service. Ground loading and road transportation systems with exemplary safety records are currently serving both the commercial and government sectors of the economy.

Some experimental aircraft programs using hydrogen (fig. 97) have been completed and are in progress. These programs have primarily involved converting or developing air-breathing engines for use with liquid hydrogen as the fuel. Assuming that liquid hydrogen can be manufactured and distributed at an acceptable cost, it is an interesting concept for subsonic aircraft; however, there are obvious questions related to airframe design, the propulsion system, structural materials, flight and ground operations, and operating costs.

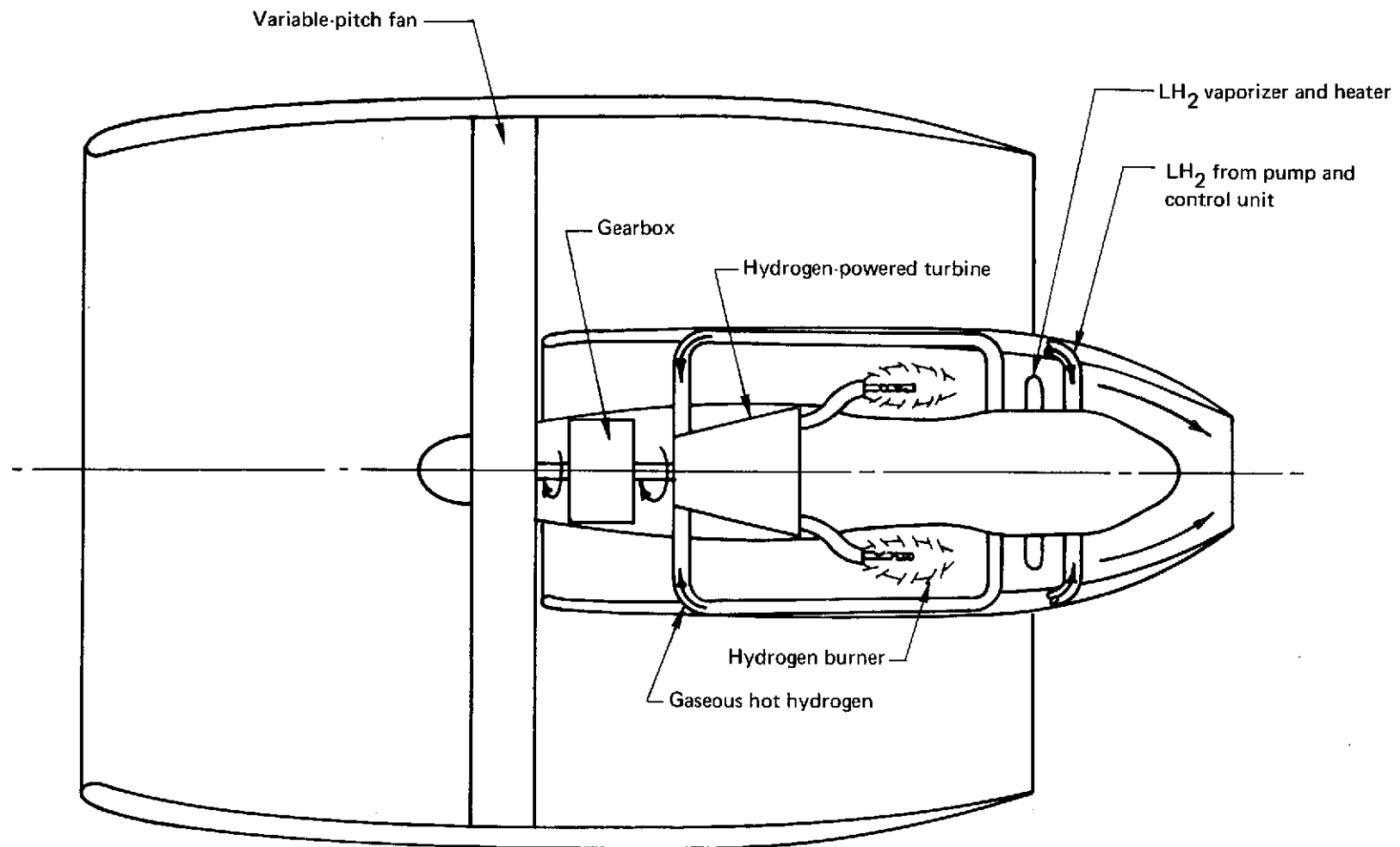


FIGURE 97.—HYDROGEN-FUELED ENGINE



#### 4.4.10.3 Recommended Action

A two-phase program is recommended leading to the technology development of using hydrogen fuel for subsonic aircraft and a flight test evaluation and development of a hydrogen fuel system for an available aircraft.

Phase I would assess the feasibility and advantages of using hydrogen fuel for subsonic aircraft and assess the problems and technology requirements peculiar to hydrogen-fueled subsonic aircraft.

The following aspects of aircraft and systems shall be considered:

- a)  $\text{LH}_2$  tankage design concepts
- b)  $\text{LH}_2$  insulation requirements and design concepts
- c) On-board fuel system (e.g., plumbing, pressure, and flow regulation)
- d) Unique problems due to  $\text{LH}_2$  (e.g., temperature-cycling effects on structural fatigue)
- e) Interaction of aircraft with  $\text{LH}_2$  ground storage and handling procedures
- f) Propulsion system/airframe integration
- g) Interaction of aircraft with ground-support equipment
- h) Production and maintenance costs
- i) Safety (e.g., aspects involved with tank compartment inert purge system during flight and ground service, as well as special fuel system protection that may be required for crash conditions).

Phase II would be a future follow-on program that would evaluate and develop the airplane loading techniques and in-flight operating procedures using a 737-type airplane converted for use with  $\text{LH}_2$  as fuel.

#### 4.4.10.4 Cost and Schedule

Phase I would consist of a 6-month program (fig. 98) estimated to require a total funding of \$300,000.

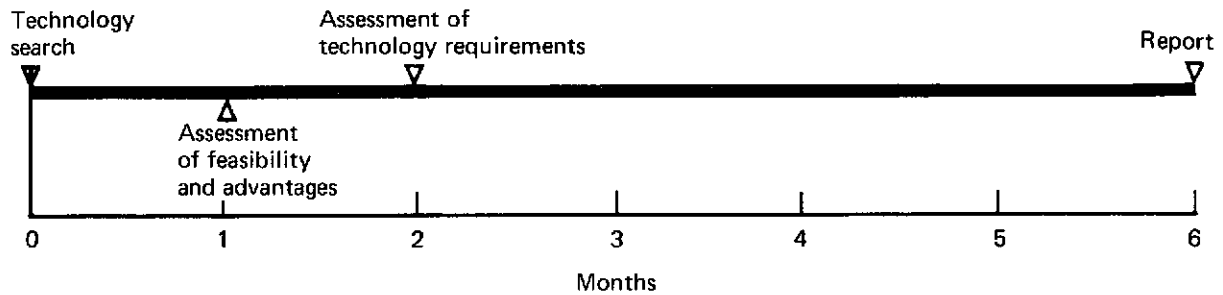
WORK STATEMENT (PHASE I)

- Assessment of feasibility and advantages of hydrogen fuel
- Assessment of problems and technology requirements

PAYOFF

- Lowered pollution
- Future fuel availability

SCHEDULE



*FIGURE 98.—LH<sub>2</sub> AS A COMMERCIAL AIRPLANE FUEL*  
RESEARCH AND TECHNOLOGY SUMMARY

Boeing Commercial Airplane Company

P.O. Box 3707

Seattle, Washington February 15, 1974

## REFERENCES

1. Final Report—Study of the Application of Advanced Technologies to Long-Range Transport Aircraft, Volume I—Advanced Transport Technology Final Results. NASA Contract NAS1-10703, May 1972.
2. Final Report—Study of the Application of Advanced Technologies to Long-Range Transport Aircraft, Volume II—Advanced Technology Program Recommendations. NASA Contract NAS1-10703, May 1972.
3. SST Passenger Ride Quality Criteria Analysis. D3-7600-7, February 1969.